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ULTRAVIOLET BACKGROUND RADIATION

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March 1991

Preprint Number 79

Preprint Series

20100827238

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Bloomberg Center for Physics & Astronomy
Baltimore, Maryland 21218

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Accepted for publication in *Annual Review of Astronomy and Astrophysics*.

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Annual Review of Astronomy and Astrophysics

Volume 29, 1991

in press

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1. CONTEXT

1.1 *The Cosmic Background Spectrum*

The topic is the diffuse cosmic ultraviolet background radiation, which is one among a number of diffuse celestial backgrounds that occur at various frequencies. For an excellent earlier review, see Paresce & Jakobsen (89). Figure 1 provides a key for the introductory discussion of the context within which the ultraviolet background occurs.

The units of Figure 1 are essentially the same as those used in a similar diagram by Longair (63). Diffuse background radiation units that are used by most observers of the ultraviolet background are photons $\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{\AA}^{-1}$; such units will be referred to simply as "units" throughout this article. There are those that express surface brightness as νI_ν , where the units of I_ν are $\text{ergs cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{Hz}^{-1}$ (e.g. 94). When multiplied by a (constant) factor of 5×10^7 , these are "units."

Referring to the circled numbers in Figure 1, the various diffuse backgrounds are as follows:

1. The continuum radio background (74), which has a spectrum described by Yates & Wielebinski (117). This background has its origin in synchrotron radiation from cosmic-ray electrons that are traversing the magnetic field of the galaxy. The downturn in the spectrum at the lowest frequencies is caused by free-free absorption by the ionized component of the interstellar gas.

2. The microwave cosmic background radiation, discovered by Penzias & Wilson (95). The spectrum is blackbody emission at $2.736 \pm 0.017 \text{ K}$ (28; see also 69).

3. Emission from cold interstellar dust. This has been observed by *IRAS* as the $100 \mu\text{m}$ cosmic cirrus (64). The existence of such dust at moderate and high Galactic latitudes will be of great interest in our discussion of the origin of the diffuse ultraviolet background.

4. The predicted integrated emission from redshifted galaxies; two extreme models are shown.

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5. Emission from hot dust in the solar system. This has been mapped, at 12 μm and 25 μm , using *IRAS*.

6. Optical background radiation, which is dominated by zodiacal light: solar photons scattering from interplanetary dust.

7. This curve is a prediction, by Weymann (115), of the spectrum of optical, ultraviolet, and X-radiation that is expected from a dense ionized intergalactic medium, if such exists, for a certain history of the reheating of that medium (see also 50). The large bump is HI 1216 Å Lyman α radiation, redshifted into the visible, while the narrower bump is HeII 304 Å radiation, redshifted to about 1500 Å. Region 7 includes the spectral region of the present review; an enlargement, for more detailed description of our context, appears in Figure 2.

8. The X-ray background, discovered by Giacconi et al (26), and reviewed by Boldt (7). While the spectrum is exquisitely free-free in shape, the perfect blackbody spectrum of the microwave background (Region 2) almost eliminates the possibility that these X-rays are, in fact, radiation from a very hot intergalactic medium (99); the origin therefore remains a mystery.

9. The gamma ray background. The diffuse Galactic gamma-ray emission is reviewed by Bloemen (4).

A magnified view, in the same units, of the most immediately relevant portion of the universal cosmic background spectrum appears in Figure 2. The theoretical spectrum of Weymann is repeated. The hatched region at highest energies is the cosmic X-ray background that has been reviewed by Boldt (7), while the observations of Henry et al (38), Davidsen et al (19), and those reviewed by Silk (104) show the sharp rise that is the low-energy diffuse X-ray background. This subject was reviewed recently by McCammon & Sanders (71). The mechanism is emission from fairly local interstellar gas.

There is a "censored" region, from 912 to about 44 Å, over which we cannot observe the true cosmic diffuse background because of the very high opacity of the local interstellar medium (78). This high opacity is caused by photoionization of the

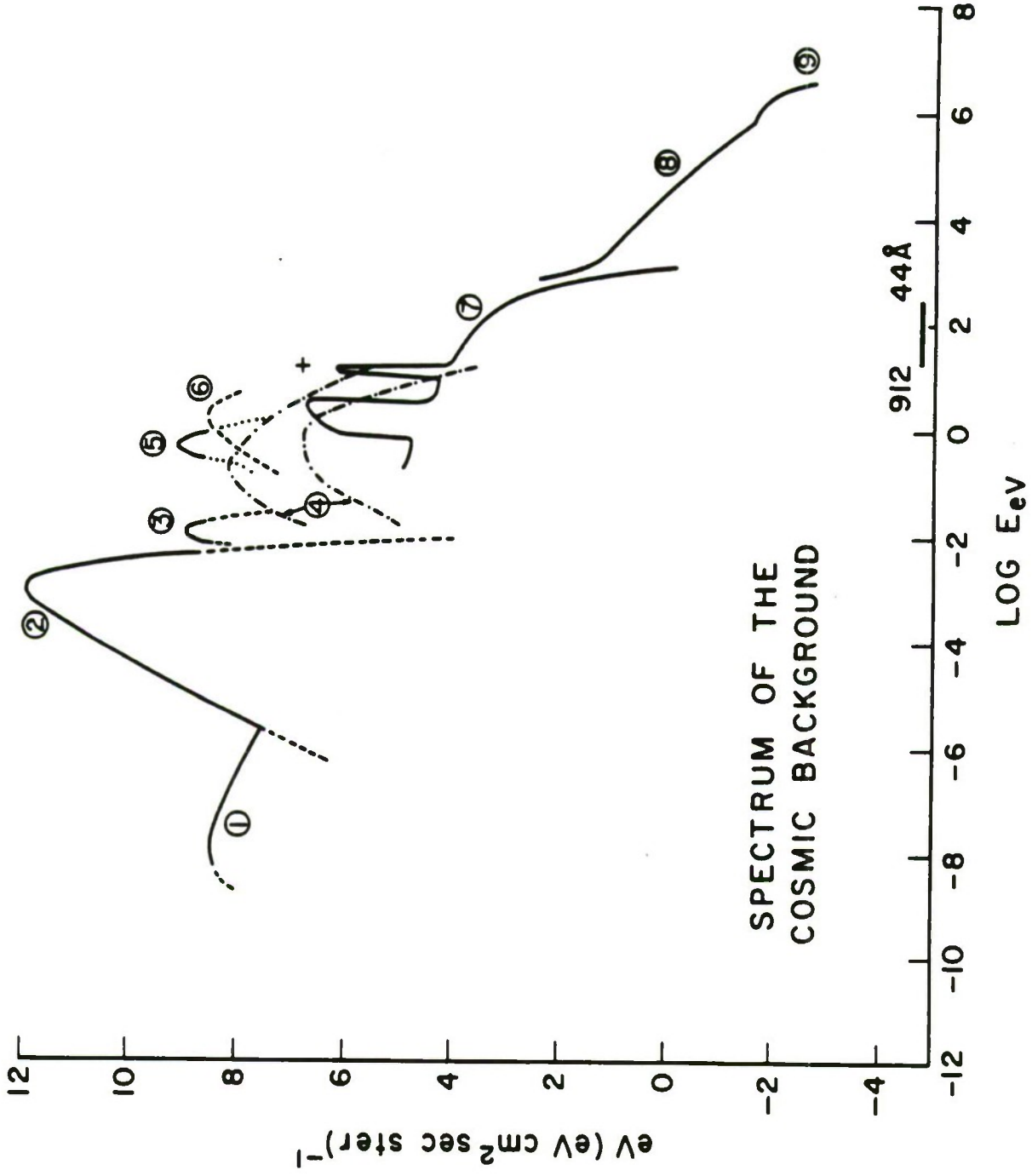


Figure 1 Diffuse background radiations extend from the radio (circled number 1) to gamma rays (circled 9). The + sign identifies the general spectral region that is the subject of the present review.

interstellar gas. This "censored" region is shown by a heavy bar near the abscissa in Figure 1; it is bounded by a vertical bar at 912 Å in Figure 2. The extreme efficacy that is expected of the censorship can be seen by considering the dashed line in Figure 2 which shows the expected attenuation by the interstellar gas toward the Galactic pole of Weymann's predicted spectrum. A true diffuse background probably does occur in this energy range, arising from emission from the hottest component of the interstellar medium itself. A comprehensive summary of the observations is provided by Labov, Martin & Bowyer (59), and reviews of the relevant astronomy, which is the local interstellar medium, are given by Holzer (45) and Cox & Reynolds (18). Hence the subject is not discussed further here.

The spectral region to be discussed in what follows ranges from the end of the visible spectrum around 4000 Å, down to 912 Å; with greatest emphasis on the still more limited spectral region between 2500 and 912 Å. How could such a very small wavelength range, which occupies only a minute segment in Figure 2, deserve the attention it receives in this volume of the *Annual Review of Astronomy and Astrophysics*?

1.2 The Importance of the Diffuse Ultraviolet Background

There are two reasons why diffuse emission in this narrow band is of great importance. The first is that a host of disparate, quite unconnected emission sources are either known to exist, or might exist, which could contribute to this diffuse background. Measurement of these emissions would greatly improve our understanding in many areas of astronomy and astrophysics.

The second reason of even greater potential importance is that the sky may be truly outstandingly black in the far ultraviolet, offering a "dark site" that is unprecedented in astronomy. Figure 3 is from a discussion of this by O'Connell (85). From 2500 Å to longer wavelengths O'Connell's figure shows that the cosmic diffuse background is dominated by zodiacal light. This is why we concentrate here on the region from 2500 Å down to 912 Å; nevertheless, the zodiacal light is of considerable interest in its own right, and so the state of these observations also will be mentioned in what follows.

Shortward of 2500 Å, O'Connell shows "diffuse galactic light" as the source of the cosmic ultraviolet background, with an average

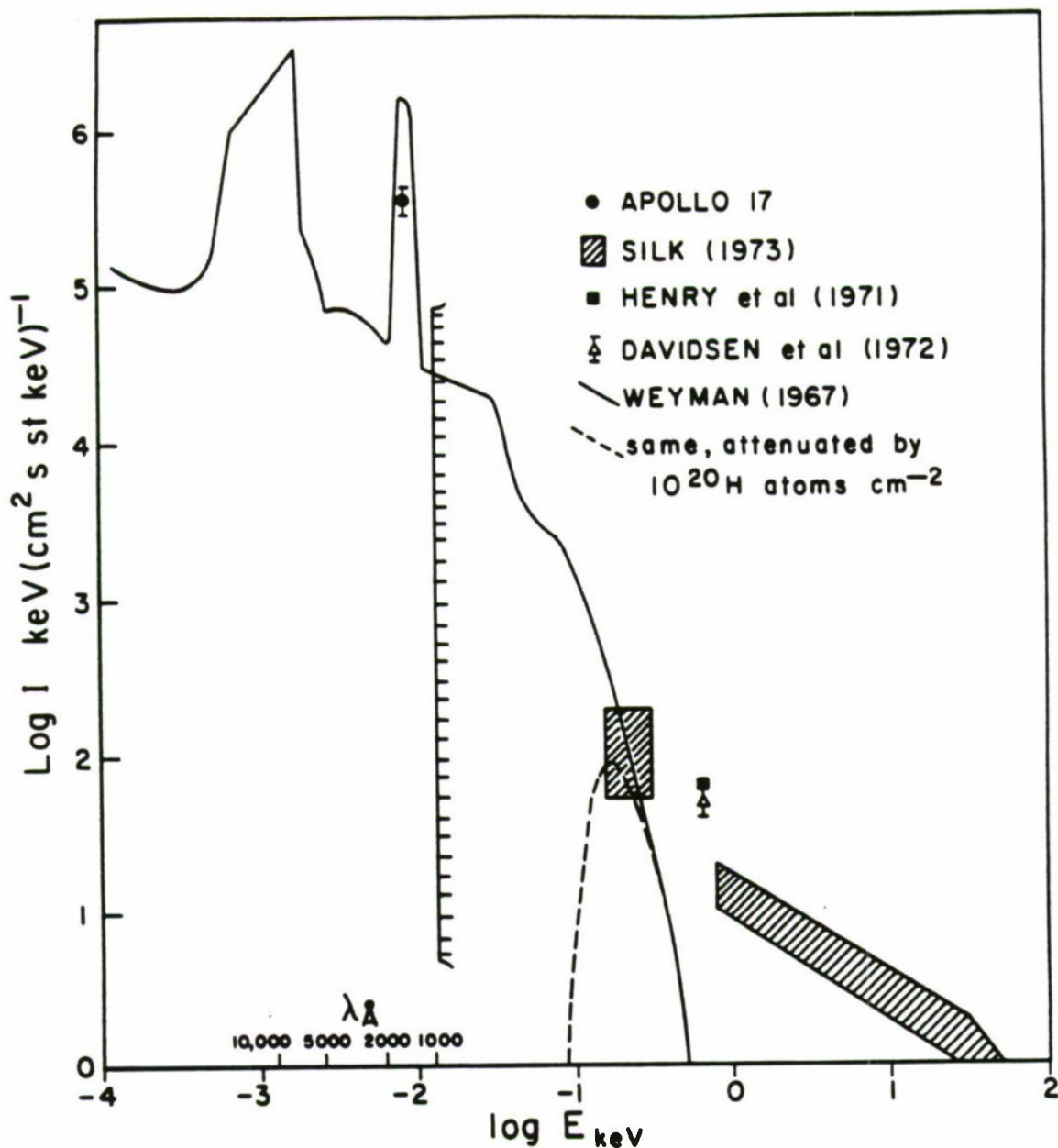


Figure 2 (A magnified view of part of Figure 1.) The *Apollo 17* point is the cosmic background measurement of Henry et al (37). The solid curve is one prediction, by Weymann (115), of emission from hot ionized intergalactic matter. The hydrogen ionization edge at 912 Å is indicated by a vertical hatched line; shortward of this wavelength, the interstellar medium is almost opaque (78), as illustrated in the attenuation (*dashed line*) of the Weymann model.

level of emission of 25.5, in his units, which corresponds to about 1000 units at 2000 Å. But there are very great disagreements among various observers as to what the actual brightness of the sky is at these wavelengths at moderate and high Galactic latitudes. Most observers do agree that there are many places at high Galactic latitudes where the diffuse background is <300 units. The details of the various observations, and their disagreements, form the bulk of the present review, but the point to be made here is that O'Connell is probably more than a magnitude conservative in Figure 3, in the sense that the sky is probably even blacker at moderate and high latitudes, in the ultraviolet, than O'Connell suggests.

Why is this darkness important? First, examine the 4000 to 6000 Å spectral range in Figure 3. In this range, the improvement in background that can be expected for Space Telescope over the background experienced by ground-based observatories is only about one magnitude. Space Telescope will make its greatest improvement in detecting faint point sources (once the replacement wide-field/planetary camera is installed), by concentrating the light of point sources and thus increasing their detectability against the zodiacal light background. But in the ultraviolet, as O'Connell shows, the background itself is reduced by perhaps four magnitudes compared with the visible!

This makes the degradation of the usefulness of the European Faint Object Camera on the Hubble Space Telescope tragic, with no replacement planned, but it also makes clear the enormous promise for the future *if an intensely black ultraviolet sky* at moderate and high Galactic latitudes, in fact, exists.

There is also the question of detection of extended objects, and in particular, objects of very low surface brightness. O'Connell concludes, "taking into account the UV/V energy distributions of potential targets, we find that in certain favorable circumstances UV photometry may permit the detection of regions with equivalent V band surface brightnesses as low as 35 mag arcsec⁻², or over 100,000 times fainter than the ground-based night sky. We consider applications of UV surface photometry to the study of circumgalactic regions, dwarf galaxies, low-surface-brightness spirals, and the detection of primeval galaxies...."

Of course even the darkest sky is of no use, unless there are sources of interest radiating in the spectral band where the dark sky

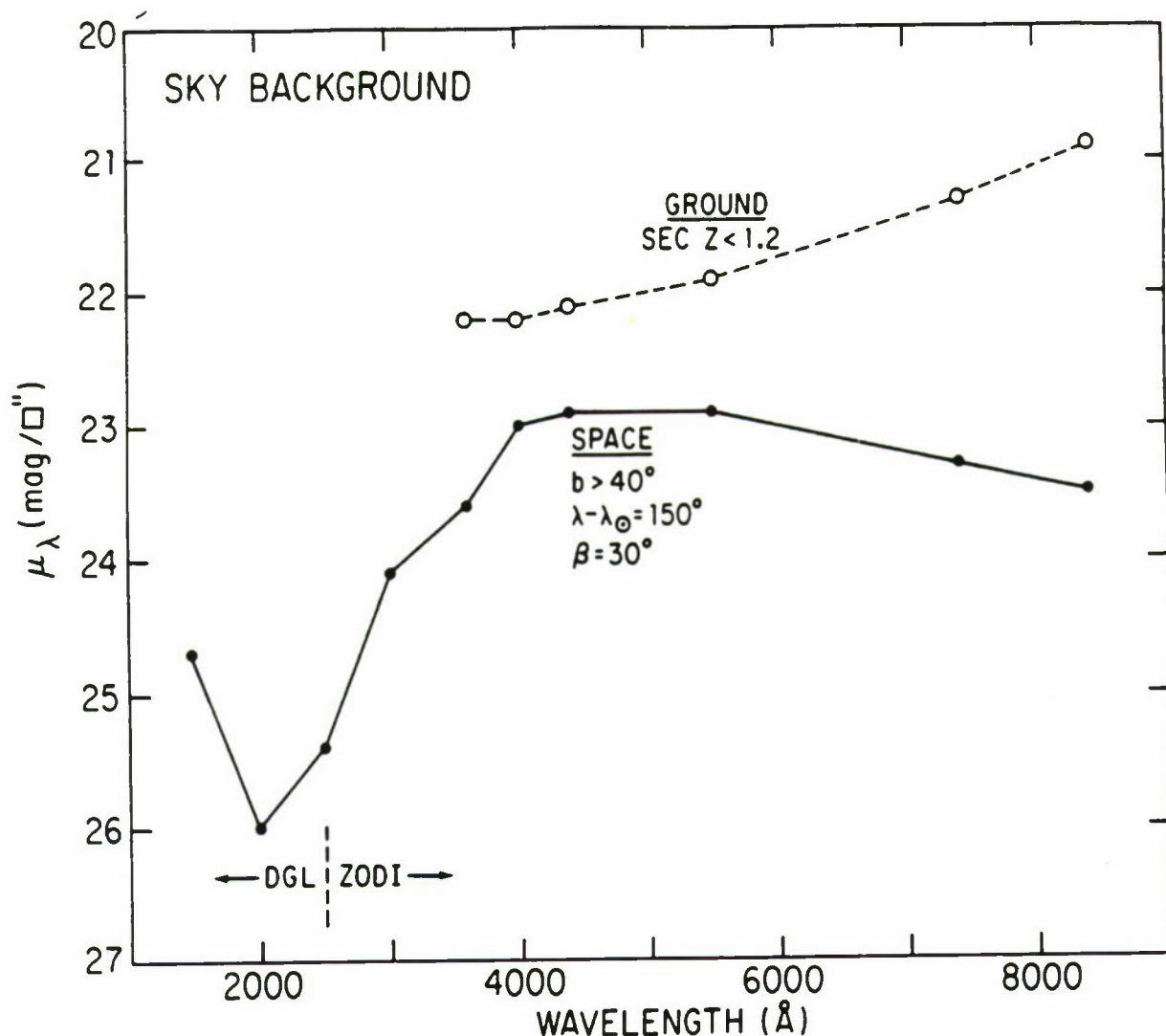


Figure 3 Estimated spectral energy distribution of the night-sky background near the zenith at an excellent ground-based site on a moonless night and in a direction typical of extragalactic pointings in space. The curves are plotted in monochromatic magnitude units. The wavelength at which the diffuse Galactic light (DGL) and zodiacal (ZODI) contributions to the space background are comparable for this pointing direction is indicated, and the arrows indicate the regions of dominance of one or the other. Effects of individual strong skyglow emission lines are not included, but the combined effect of OH emission bands on the ground is evident for $\lambda > 7000 \text{ Å}$ [Figure and adapted caption from O'Connell (85), with permission].

occurs, and O'Connell considers that point, as may be seen from the above quote. Some very faint galaxies are blue (12, 112). Also, our knowledge of galaxies is heavily biased by the sky background (20). Low-surface-brightness galaxies have been discovered (9, 96). Now, our spectral region includes the resonance line of the most abundant atom in the universe, hydrogen. This line, Lyman α , is at 1216 Å. Observations right at 1216 Å are severely impeded by local (solar-system) sources of Lyman α (see below), but for moderate redshifts, Lyman α that is emitted by galaxies, by the intergalactic medium if any, or by as yet undiscovered objects lies in "the black hole," of the intensely dark ultraviolet sky. But does this darkness exist? What now is necessary is a discussion of the status of the relevant observations.

The field of diffuse ultraviolet background radiation is controversial for two reasons: first, the observations are difficult, for reasons to be explained; and second, each set of observations is necessarily the result of a space experiment, which is costly both in dollars and in human investment, and there is then even more intensity than customary in defending data, some of which must be incorrect because different data sets are contradictory. In this regard, consider the comment by Bondi (8): "while in observational work it is unfortunately considered somewhat impolite for one observer to criticize the observations and immediate inferences of other observers, similar criticism between theorists is luckily considered perfectly natural". In what follows it will be necessary to discuss and criticize some of the contradictory data sets, and we do so in the spirit of Bondi.

2. A SAMPLE OF DATA

On January 12, 1986, Space Shuttle *Columbia* (in the last shuttle flight before the *Challenger* accident) carried into low Earth orbit (340 km ~circular) two separate experiments, created by two different university groups for the study of cosmic diffuse ultraviolet background radiation. In the experiments, collectively called UVX, the instruments were rigidly co-aligned to insure that the same part of the sky was observed by both. The Berkeley group had previously reported many extraordinarily bright patches of diffuse ultraviolet background, at high galactic latitudes. The Johns Hopkins group had consistently reported much lower intensities for the diffuse background at all moderate and high

Galactic latitudes. The purpose of the *UVX* experiment was to address this fundamental contradiction.

The result of this parallel experiment with comparisons is described below; but first we consider the Johns Hopkins *UVX* data in detail because we shall use it as a template to address the technical difficulties that are faced by all observers of the diffuse cosmic ultraviolet background.

Figure 4 shows the Johns Hopkins data for target 9, called SPECTRUM, which has been described by Murthy et al (81, 82). The corresponding identical Berkeley target is called by them either number 8 (67, 68) or number 9 (47).

This SPECTRUM target is a region from Galactic latitude 86° (start of scan), to 74° , at Galactic longitude 335° . Time increases up the page. The scan represents about 20 minutes of data taken while the spectrometers scanned a fairly blank region of the sky. What is shown in Figure 4 is a spectrum of the entire area, obtained by scanning the slits of the spectrometers in latitude with time. Slit width was 0.3° on the sky, while spectral resolution was 17 \AA in the short-wavelength (1200-1700 \AA) spectrometer and 27 \AA in the longer-wavelength (1650-3100 \AA) spectrometer. Wavelength increases from 1216 \AA (the very bright Lyman α emission line that is observed throughout the whole course of the scan) on the left to 3200 \AA at the right edge of the figure.

Using Figure 4 we now discuss the various sources of noise that the observer of cosmic diffuse background must contend with. This is done in some detail to appreciate the difficulty of the observations and therefore to assess reliability when we examine the data, to determine which should be trusted.

2.1 *HI 1216 \AA Lyman α Radiation*

The Lyman α line is the radiation seen along the left edge of Figure 4. Its origin is terrestrial and solar system, not cosmic. It is vastly brighter than appears in Figure 4, because there it has been greatly attenuated by the presence, in the optical system, of a CaF_2 filter designed to block it. That filter also totally excludes radiation with wavelengths shorter than Lyman α ($L\alpha$). The loss of this radiation for the present study is the price paid here to be free



Figure 4 A sample of spectral data from the Johns Hopkins UVX cosmic background experiment. Time increases up the page; wavelength is from Lyman α (bright emission line at the extreme left, 1216 Å) to 3200 Å at the right edge of the photograph. Intense airglow is seen early in the spatial scan at the longest wavelengths (*lower right*). As the spatial scan proceeds, stars (*horizontal bands at long wavelengths*) enter and leave the field of view, and two airglow lines of variable intensity are seen near Lyman α . Zodiacal light (*faint vertical bands at far right*) appears throughout the spatial scans at an intensity of ~1500 units. The vertical discontinuity in the middle of the figure shows that most of the residual signal is due to instrumental dark current in the two spectrometers.

of intensely bright $L\alpha$ radiation scattering within the spectrometer. The problem, of course, is that there is no such thing as a perfect grating; any grating will scatter some of the $L\alpha$ to other wavelengths, where it might be misinterpreted as true cosmic continuum background at the nominal wavelength.

Even if $L\alpha$ is admitted to the spectrometer, it is to some extent possible to correct the data at other wavelengths for the scattered $L\alpha$. Edelstein (21) is able to strongly suppress the reflectivity of optics at and near 1216 Å, which will permit study of shorter wavelength radiation with much less significant interference from scattered $L\alpha$; in addition, gratings with superior scattered-light properties are now available.

The source of the annoying $L\alpha$ is sunshine. The solar system is bathed in ($L\alpha$) sunshine, even at night. Solar $L\alpha$ photons scatter from the hydrogen upper atmosphere of the Earth, multiply scattering to the night side of the Earth. Furthermore, solar $L\alpha$ photons scatter back from the interstellar neutral hydrogen gas that is flowing through the solar system.

It is possible to reduce the $L\alpha$ sky brightness substantially by removing the spectrometer to the far reaches of the solar system, as was done for the *Voyager* far-ultraviolet spectrometers, discussed below.

2.2 Radiation from Terrestrial O I

Terrestrial O I 1304 Å resonance radiation is quite apparent in Figure 4 toward the end of the scan in latitude, and is present to some extent throughout that scan, while terrestrial O I 1356 Å produced by electron-ion recombination is also faintly present. The altitude dependence of this latter mechanism was measured by Brune et al (13). One example of these fundamental "engineering" data required to *reduce* raw data appears in Figure 5. Experiments (e.g., 57) that are planned for above 500 km in altitude should experience no problems due to O I.

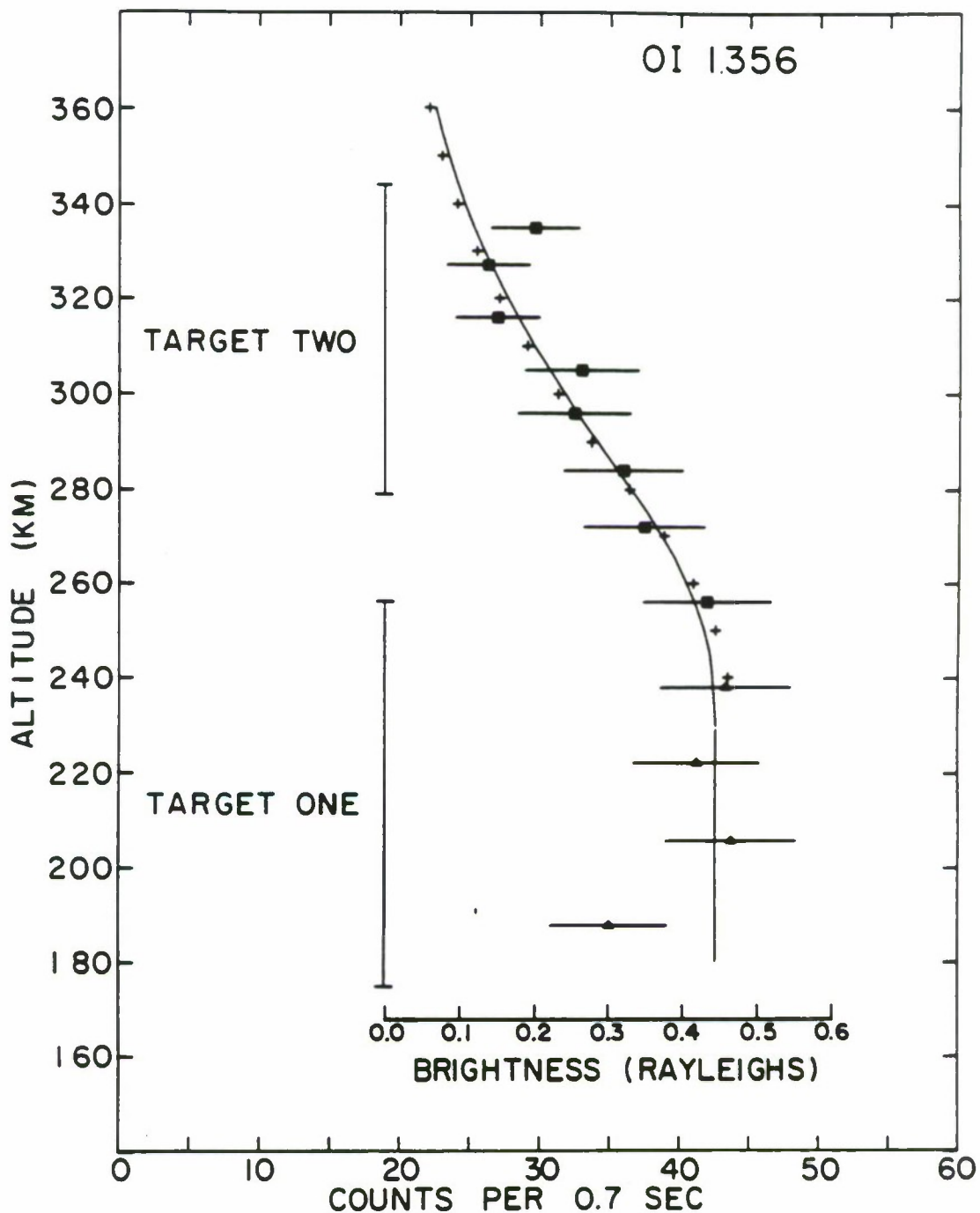


Figure 5 Oxygen 1356 Å altitude profile data from an *Aries* rocket experiment (13). Above 360 km altitude, oxygen emissions should not significantly interfere with cosmic ultraviolet background experiments.

2.3 Radiation from Terrestrial NO

Intense terrestrial NO γ - and δ -band radiation, as well as O₂ radiation due to chemical recombination, is present in Figure 4 near the beginning of the scan, in the wavelength range 1900 to 3200 Å. The terrestrial NO spectrum and altitude dependence were measured by Tennyson et al (108) and the result is shown in Figure 6. At the UVX altitude of 340 km, terrestrial NO emission when looking away from the Earth is not expected to be a problem. The spectrometer line of sight at the beginning of the scan in Figure 4 intersected the terrestrial limb, which accounts for the strong spectrum that is seen in the lower right hand part of the diagram.

Most terrestrial line emissions are quite unimportant beyond 500 km for example. It should be kept in mind that many measurements that have been hoped in the past to be of the diffuse cosmic ultraviolet background *have been made from much lower altitudes*. If in such cases a spectrometer is used (as in Figure 4), there is no great difficulty in separating the unwanted noise from true signal. In contrast, if broad-band photometers are used - as has often been the case - it is much more difficult to make the case that one understands the physical origin of the count rate that emerges from the apparatus.

2.4 Shuttle Glow

The effects of terrestrial atmospheric emission are pernicious. In 1980, Huffman et al (46) reported intense Lyman-Birge-Hopfield emission of N₂ over a very broad spectral range observed looking down from a satellite in polar orbit at altitudes from 160 to 260 km. Fortunately the signal appears to have had its origin not directly from the atmosphere, but rather from impact of the residual atmosphere on the spacecraft (16). This phenomenon became famous within the Space Shuttle program as "shuttle glow" (73). The data of Figure 4 and other UVX data from The Johns Hopkins experiment have been used by Tennyson et al (109), and Morrison et al (77) to show that the Space Shuttle, even with shuttle glow, is a most benign environment for a properly managed study of very-low-surface brightness ultraviolet radiation.

Discrepancies between different observations, discussed below, may be related to this phenomenon of spacecraft glow. The argument for or against this possibility in specific cases is

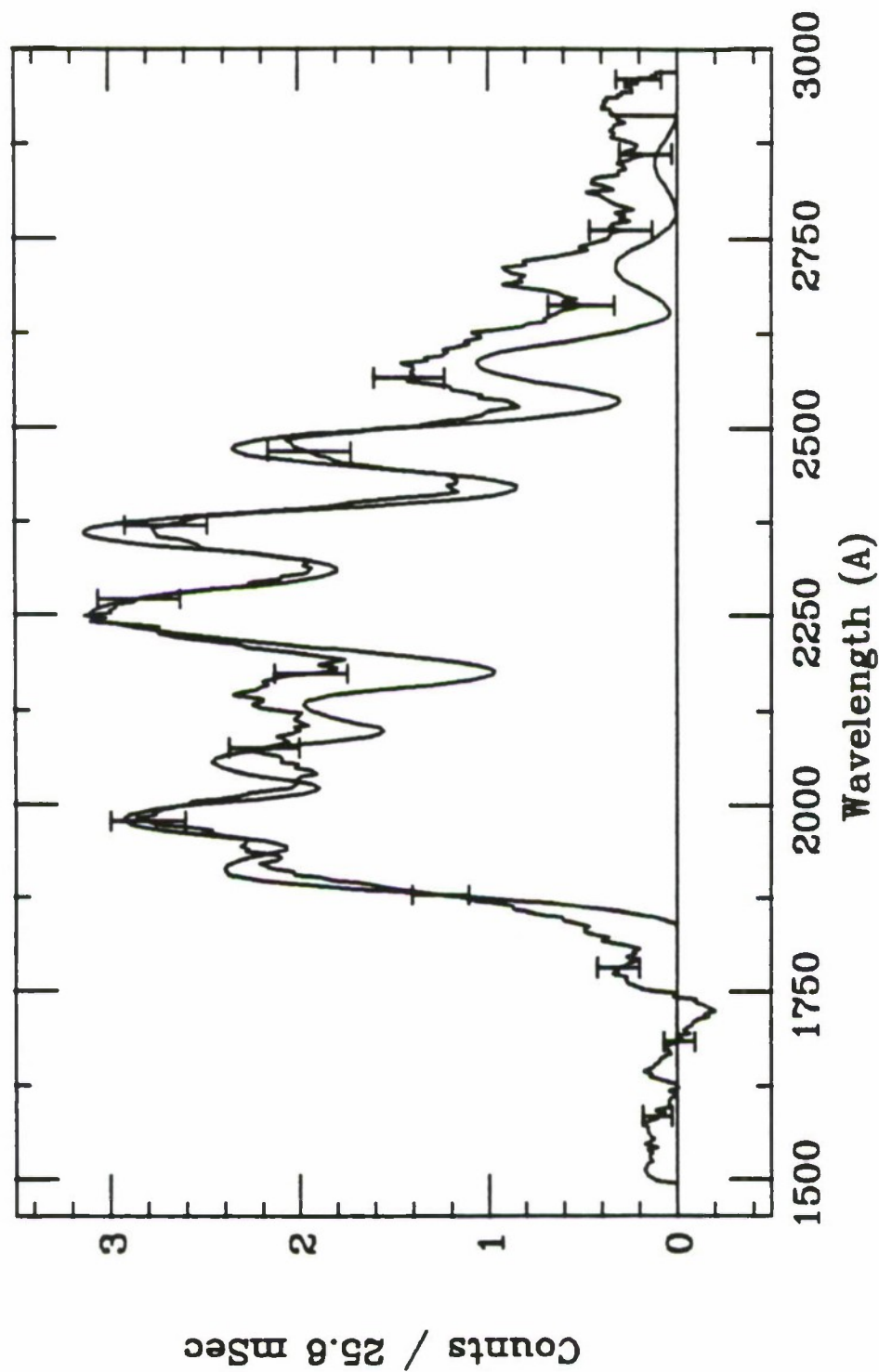


Figure 6 NO γ - and δ -band emission as measured by Tennyson et al (108) who also obtained altitude profiles for the various emissions. Above 250 km or so, NO emission should not be a problem for upward-looking observers.

inconclusive, especially when a photometer is used and there is therefore no diagnostic character to the signal being reported.

2.5 Stars

Several point sources (stars) appear in Figure 4 and then disappear as the spatial scan proceeds. These spectra are evident in the figure as horizontal bands of emission, strongest at the longest wavelengths and fading out at the shortest wavelengths.

These stars are, of course, a nuisance as they are noise in the background that is sought. But they can be much worse than a nuisance, for if one's spectrometer or photometer has no imaging capability, as is the case in the majority of past experiments, radiation from a star that is in the field of view but that is not *known* to be in the field will be misinterpreted as diffuse ultraviolet background radiation. And since there are many more faint stars at low Galactic latitudes, the false background that is inferred will correlate nicely with Galactic latitude. This problem is discussed specifically as we describe the various experiments in what follows. Here, we simply give a general characterization of the spatial and spectral character of the stellar ultraviolet sky.

The appearance of that sky as predicted in a previous study (30) is shown in Figure 7, which is a map of the sky at 1482 Å, in Gould coordinates. Gould coordinates are galactic coordinates tipped by about 19°. Figure 7 shows that they are the physically meaningful system for this problem - the stars that are contributing most of the ultraviolet light are located in the Gould belt, *not* in the galactic plane. Observational confirmation that the sky has the predicted appearance came from a rocket flight (39), from which the data shown in Figure 8 were obtained. Figure 8 is oversaturated, unlike Figure 7. This has been done to bring out fainter surface brightnesses more clearly. Additional confirmation of the Figure 7 prediction was obtained by Gondhalekar, Phillips & Wilson (27) who mapped all of the stars observed with the S2/68 experiment (6) on the *TD-1* satellite. The difference between their observational map and the much cruder observational map of Figure 8 - and what makes Figure 8 of extra interest - is that their map includes only the direct light of stars. In contrast, the data used to form Figure 8 were obtained with a sensitive detector having a full width at half-maximum transmission of fully 10°. This means that, in addition to the direct light of stars, Figure 8 maps diffuse radiation plus the

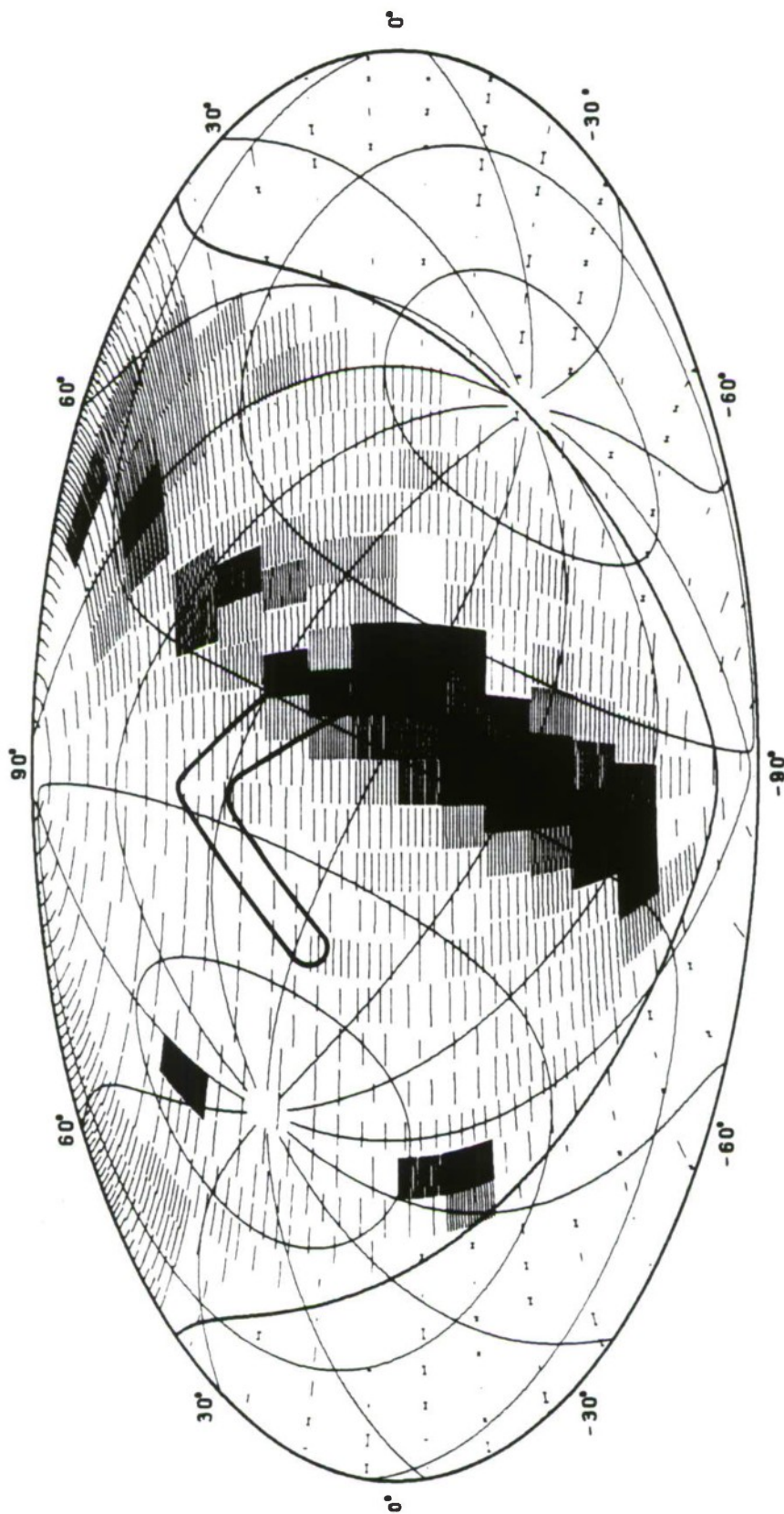


Figure 8 Observation of the sky at 1500 Å (39). The observed distribution agrees generally with the prediction of Figure 7. This map is drawn in Celestial coordinates, and a grid of Galactic coordinates is superposed. Grey scale intensity at highest latitude is 1600 units, perhaps due to residual airglow.

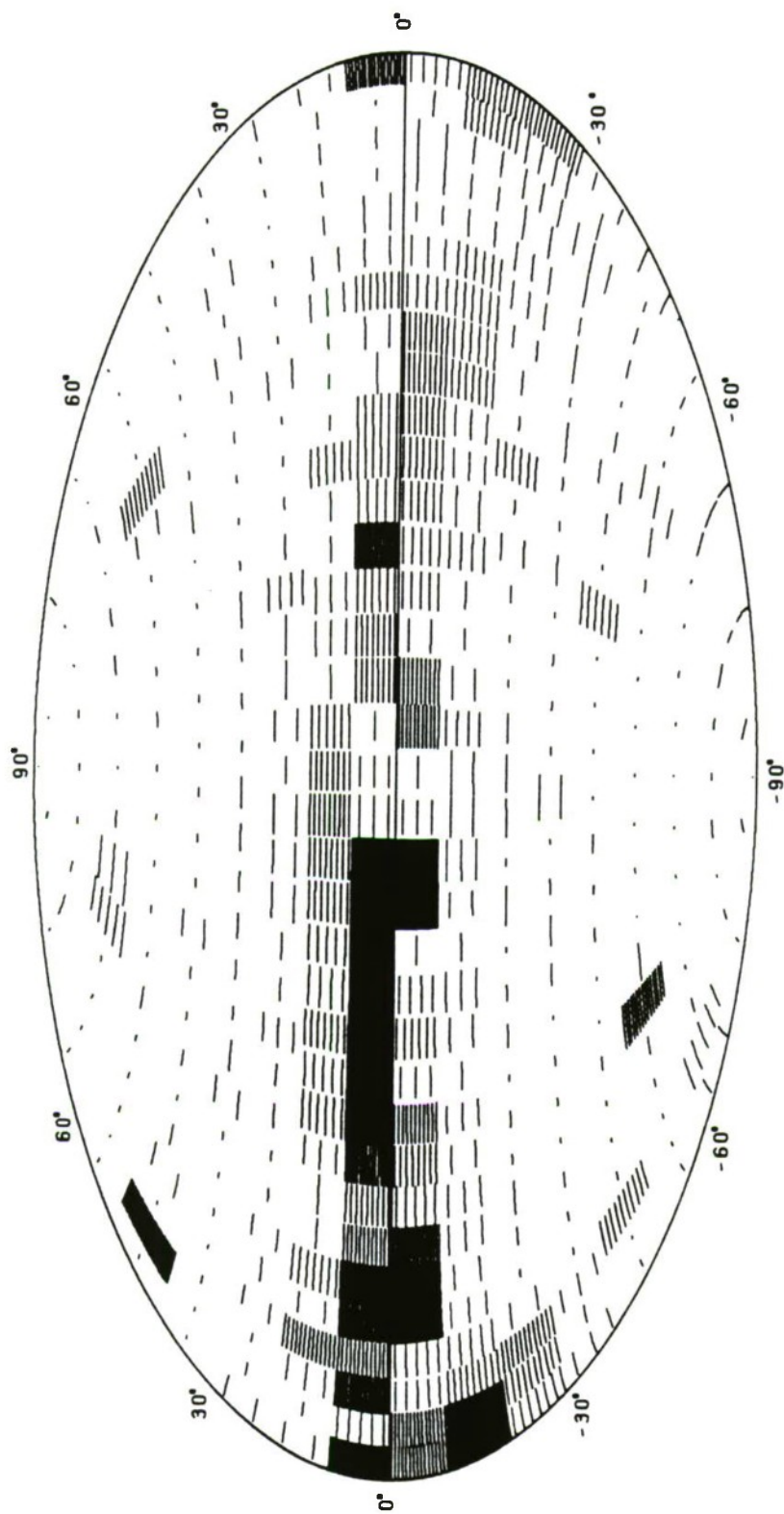


Figure 7 Predicted brightness of the sky at 1482 Å, from stars only (30). The map is drawn with Gould coordinates. Note the strong concentration of starlight to one half of the Gould plane.

integrated light of even the faintest stars. This means in turn that the faintness of the Galactic plane in regions where the Gould belt departs significantly from that plane in Figure 7 might be accounted for by incompleteness of the star catalogue from which the map was made, but the same faintness in Figure 8 is surely due to interstellar extinction. We have determined in this way that the far-ultraviolet interstellar radiation field is *totally dominated by relatively nearby stars*; hardly unexpected, but nice to have demonstrated.

One feature of Figure 7 to be noted (and that is confirmed observationally in Figure 8) is the exceedingly strong anisotropy of the local far-ultraviolet interstellar radiation field, with regard to Gould (and therefore Galactic) longitude. This anisotropy has been evaluated quantitatively using the *TD-1* data, in a painstaking study by Landsman (60). Landsman's result is shown in Figure 9, where the average surface brightness over a band of width $\pm 20^\circ$ centered on the Gould equator is plotted as a function of longitude. The flux over half the plane is as low as ~ 5000 units, and for one region of longitude it is only ~ 1000 units! This is important in what follows.

Another important feature of Figure 7 is the extreme concentration of the starlight to one half of the Gould plane. The star-catalogue integration has been plotted (30) as a function of Gould latitude. One important point in examining that plot is the comparison with the models of van de Hulst and de Jong (113), which were computed from *visible* light data.

A final remark on the problem of stars: looking back at our template again, Figure 4, we see that the *effect of stars tends to disappear at the shortest wavelengths*. This is not an instrumental effect: while Figure 4 has not been corrected for instrumental sensitivity, the sensitivity at, say, 1400 \AA is comparable to that at 2500 \AA . The explanation is that stars hot enough to contribute significantly at the shorter wavelengths are rare at moderate and high latitudes. Mentioned above (and discussed in greater detail below) is the severe danger that undetected stars pose for photometric study of the diffuse background. Figure 4 clearly shows that the danger is smallest for the shortest wavelength experiments. Above all, the danger is minimal for those experiments that have been sensitive to radiation below 1216 \AA ; namely shortward of the entire range of Figure 4.

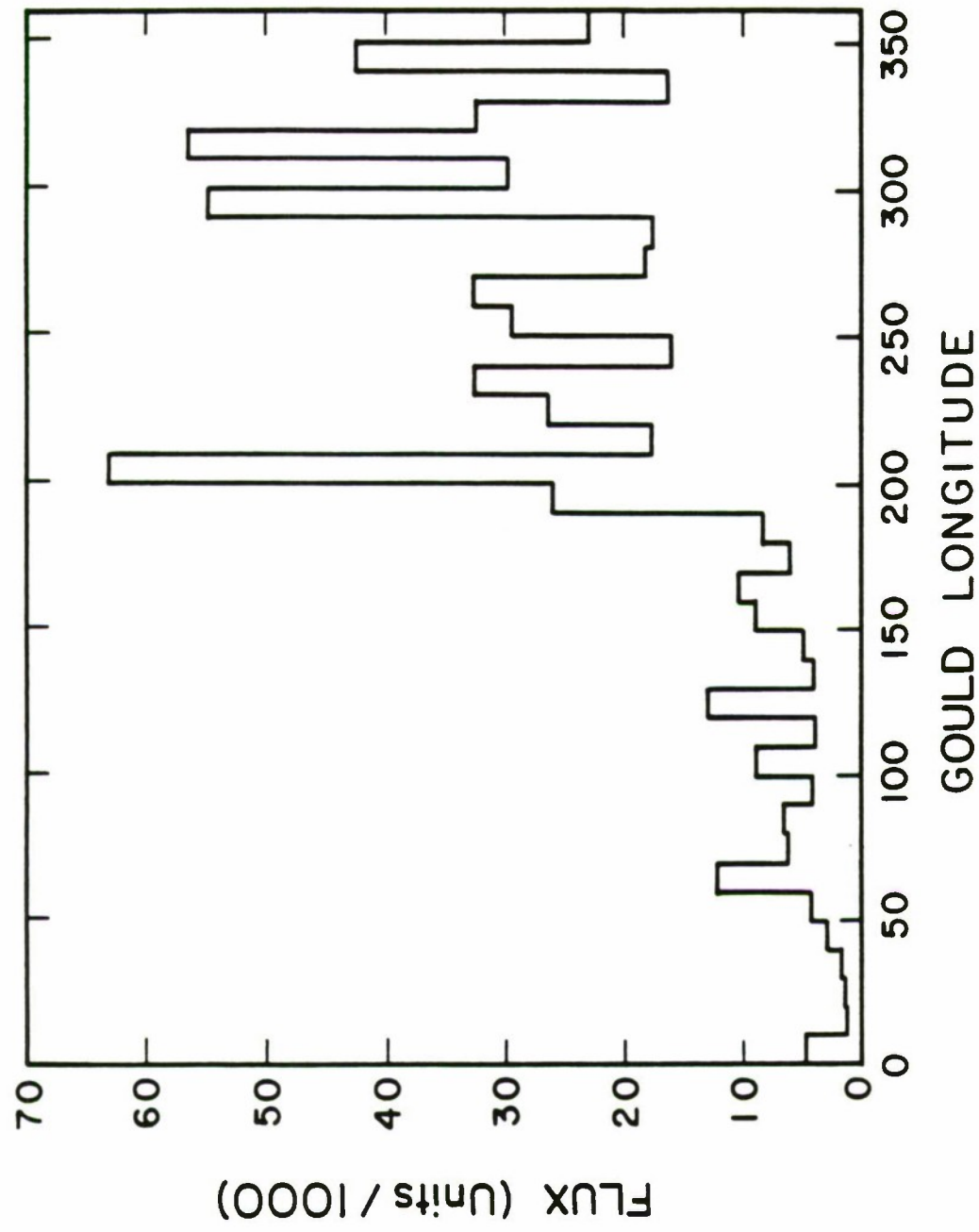


Figure 9 The anisotropy in Gould longitude that appears in Figures 7 and 8 as given by Landsman (60) who used *TD-1* data.

2.6 Dark Current

Our data in Figure 4 show a sharp break in the darkest background at a wavelength around 1600 Å near the middle of the figure. The break arises because Figure 4 has been made from the conjoined data from two independent Johns Hopkins spectrometers. The dark current was different in the two spectrometers. The central question is, what is left once this dark current is subtracted? That dark current differences are so readily apparent in the original of Figure 4 tells us at once that the accuracy of dark current subtraction is a serious matter. How serious depends quite fundamentally on the field of view of the instrument. This extremely important point must be kept in mind when considering the reliability of claimed measurements of the diffuse ultraviolet background discussed below. It can be appreciated by a numerical example. Suppose the dark current is accurately known to be 1 count per second. There is often not adequate opportunity to measure this with precision in flight, so suppose only 0.9 counts per second are subtracted from the observed signal. The artificial excess will then erroneously be attributed to diffuse ultraviolet background radiation. How large is the resulting error? Suppose, reasonably, that the efficiency is 0.01 counts per photon, that the area is 10 cm², and that the passband is 100 Å. Then the deduced spurious diffuse background, before taking into account the instrumental field of view, will appear as a flux of 0.01 photons cm⁻² s⁻¹ Å⁻¹. Now for comparison, typically reported values of the "true" cosmic background, at high galactic latitudes, are 300 units. If our instrument field of view is 4.4×10^{-2} steradians, as with William G. Fastie's *Apollo 17* experiment, our spurious background will translate into 0.2 units, which is negligible. If, on the other hand, the field of view is as small as 10⁻⁵ steradians -- and this is not uncommon in past experiments (62, 75, 76, 101)-- the spurious background will be 1000 units, which of course is very serious. This problem is even more serious if the experiment is in Earth orbit rather than in interplanetary space, because the dark count rate can be highly time-variable in earth orbit due to variable impact particle flux from the Earth's radiation regions such as the South Atlantic Anomaly.

2.7 Cosmic Ultraviolet Background Radiation

In what follows we begin examining the available data, but before doing so consider again Figure 4, for comments on the true signal, rather than for the various sources of noise.

True diffuse ultraviolet background radiation is clearly present in the original of Figure 4, showing as broad, faint vertical bands in the wavelength range 2500 to 3200 Å, in the rightmost part of the figure. This is zodiacal light, and its brightness is of order 1500 units. At wavelengths shorter than 2500 Å, no signal is apparent. From this we can conclude that the true cosmic background is well below 1000 units shortward of 2500 Å. Analysis (81, 82) indicates that the average background on this target is 520 ± 200 units (1650-3100 Å Johns Hopkins UVX spectrometer) and 100 ± 200 units (1200-1700 Å spectrometer). Potential origins for this radiation are discussed below.

3. ZODIACAL LIGHT AND THE COSMIC BACKGROUND LONGWARD OF 1800 Å

In reviewing the data we consider in this and the next section the two least controversial spectral regions which are the wavelengths longward of 2500 Å where the signal is dominated by zodiacal light and the shortest wavelengths with $\lambda < 1216$ Å.

The first spectroscopic observation of zodiacal light in the spectral range 1700 to 3200 Å was made by Feldman (23). Early observations are reviewed by Tennyson et al (110). The data of Tennyson et al are themselves of considerable interest and are shown in Figure 10. They were obtained by means of a sounding rocket flight, and the spectra shown were obtained at the highest altitudes (above 257 km).

Zodiacal light (easily identifiable from its solar-type spectrum) is readily apparent in the spectrum of Figure 10, longward of 2500 Å. Also apparent, are NO γ - and δ -band emission detailed in Figure 6; but use of the altitude-dependence profiles of Tennyson et al (108) allows the extraction of an altitude-independent residual. Finally, in the spectrum there is a sharp rise at the shortest wavelengths, which carries a large error bar and which is certainly spurious -- this feature is simply a result of the sharp drop in

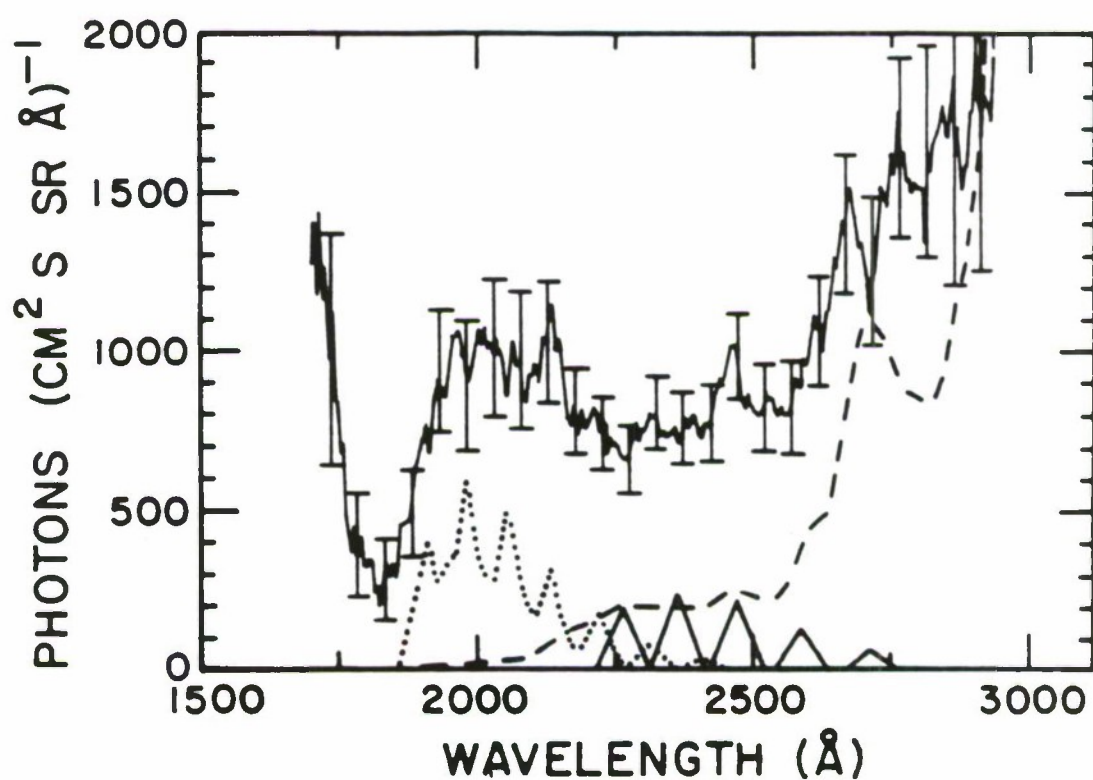


Figure 10 High altitude rocket cosmic background spectrum (*solid line with error bars*) of Tennyson et al (110) includes zodiacal light (*dashed line*) and terrestrial NO airglow emission [NO δ (*dotted line*) and γ -bands (*solid line*)]. The residual after these are removed appears in Figure 11.

experimental system transmission that occurs at the shortest wavelengths.

The match between the "zodiacal light" data in Figure 10, and the solar spectrum (*dashed line*) of Mount & Rottman (79), is not good. But similar data have been obtained in the *UVX* mission: high-quality *UVX* zodiacal light spectra which have no NO airglow problem are given by Murthy et al (82), who find excellent agreement with Mount & Rottman (except for the strange "absorption" feature at 2700 Å, and emission feature at 2800 Å, that have also been found by earlier workers). The *UVX* results show that the ultraviolet zodiacal light is much less strongly confined to the ecliptic plane than is the case for the visible zodiacal light.

In the paper by Tennyson et al (110) we concluded that zodiacal light is not the only source of cosmic diffuse ultraviolet background radiation between 2500 and 3200 Å. Upon removing the zodiacal light and NO contributions from the data of Figure 10, a residuum radiation remained as shown in Figure 11.

This residuum spectrum is approximately flat (the rise at shortest wavelengths in the spectrum of Figure 11 remains spurious) and may be the spectrum of true extra-solar-system diffuse ultraviolet background radiation. Hints of structure in the spectrum are surely spurious: consider, in Figure 10, what has been subtracted. The average intensity is 400 units. Ideas about the origin of this radiation are set out in the next section.

4. RADIATION BETWEEN 912 AND 1216 Å

The portion of the background spectrum shortward of $L\alpha$ presents special technical difficulties for its detection as described above. But the region is of particular interest. One interesting possible origin for the diffuse ultraviolet background could be redshifted hydrogen $L\alpha$ recombination radiation from an intergalactic medium or other redshifted sources, which of course will not be observed in the spectral range (blueward of $L\alpha$) that is under present consideration. In section 3, a claim was made that there exists a diffuse background, from 1750 to 2900 Å (at least) averaging 400 units. If in the range <1216 Å there is no such background, a *prima facie* case would exist that the longer-wavelength radiation

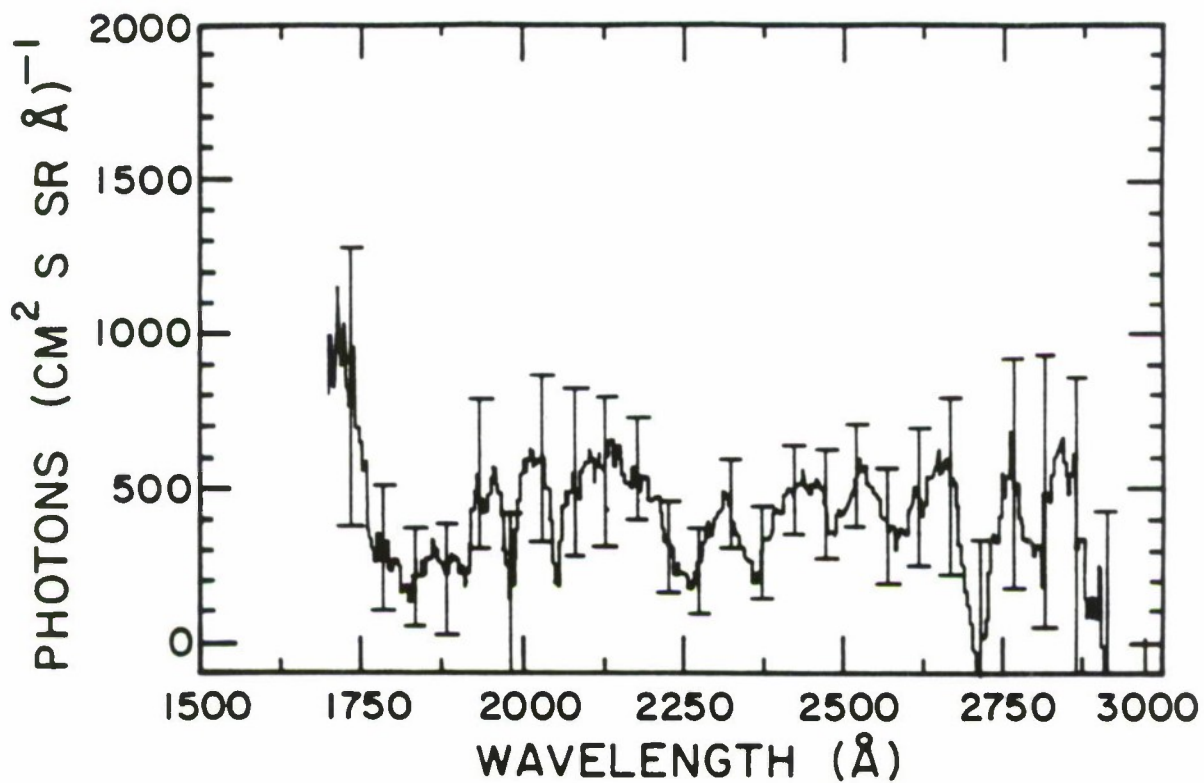


Figure 11 Cosmic ultraviolet background radiation appears flat, in these units, from 1750 to 2900 Å. The spectrum continues at about the same level down to 1216 Å, or thereabouts, and then vanishes.

(particularly if it can be shown to continue down from 1750 to 1216 Å) is redshifted $L\alpha$. With this in mind we examine the data.

While there are other important observations (e.g. 3, 88) the most comprehensive and useful are those made with the ultraviolet spectrometer on the *Voyager* spacecraft [Figure 12, from the data of Sandel et al (101) and Holberg (42)].

The *Voyager* spectrometer admits $L\alpha$, so scattered $L\alpha$ is a problem. The processing of the data is discussed well by Holberg & Barber (43) and Holberg (41) and references therein, building confidence that the results are reliable. The fact that spectroscopy is involved, rather than simply broad-band photometry, permits some real understanding of the origin of the signal.

The results shown in Figure 12 are fundamental. Upper limits are given by the lower edges of the semicircles. Notice that there are no positive detections north or south of $b = 20^\circ$. Looking only at the lowest upper limits we see evidence that above $|b| = 30^\circ$ there is no cosmic diffuse ultraviolet background brighter than 100 units. The notion that there might be a general background of 300 or 400 units at higher latitudes, as appears to exist at longer wavelengths, seems decisively excluded.

Thus, a *prima facie* case exists for the notion that the longer-wavelength ultraviolet background (described in detail below) is due to redshifted $L\alpha$ radiation, which, if present, presumably would be from slowly recombining, highly ionized intergalactic clouds.

From 912 to 1216 Å, the *Voyager* data provide only an upper limit on any background. If the longer-wavelength ultraviolet background radiation is redshifted $L\alpha$, what source might we expect for these shorter wavelengths? One intriguing potential source comes from a recent suggestion by Sciama (103), who proposes neutrinos as the dark matter, decaying with emission of photons that are just capable of ionizing hydrogen. Speculative as it may be, this notion has many attractive properties, including an explanation of the remarkably ionized state of hydrogen in the universe (72, 97, 98). Sciama's photons, if they do exist, would be created short of 912 Å, and would be seen in the 912-1216 Å range for sufficient redshift. The work of Stecker (107), Kimble et al (56), Henry & Feldman (36), and Murthy & Henry (80) describes earlier searches for

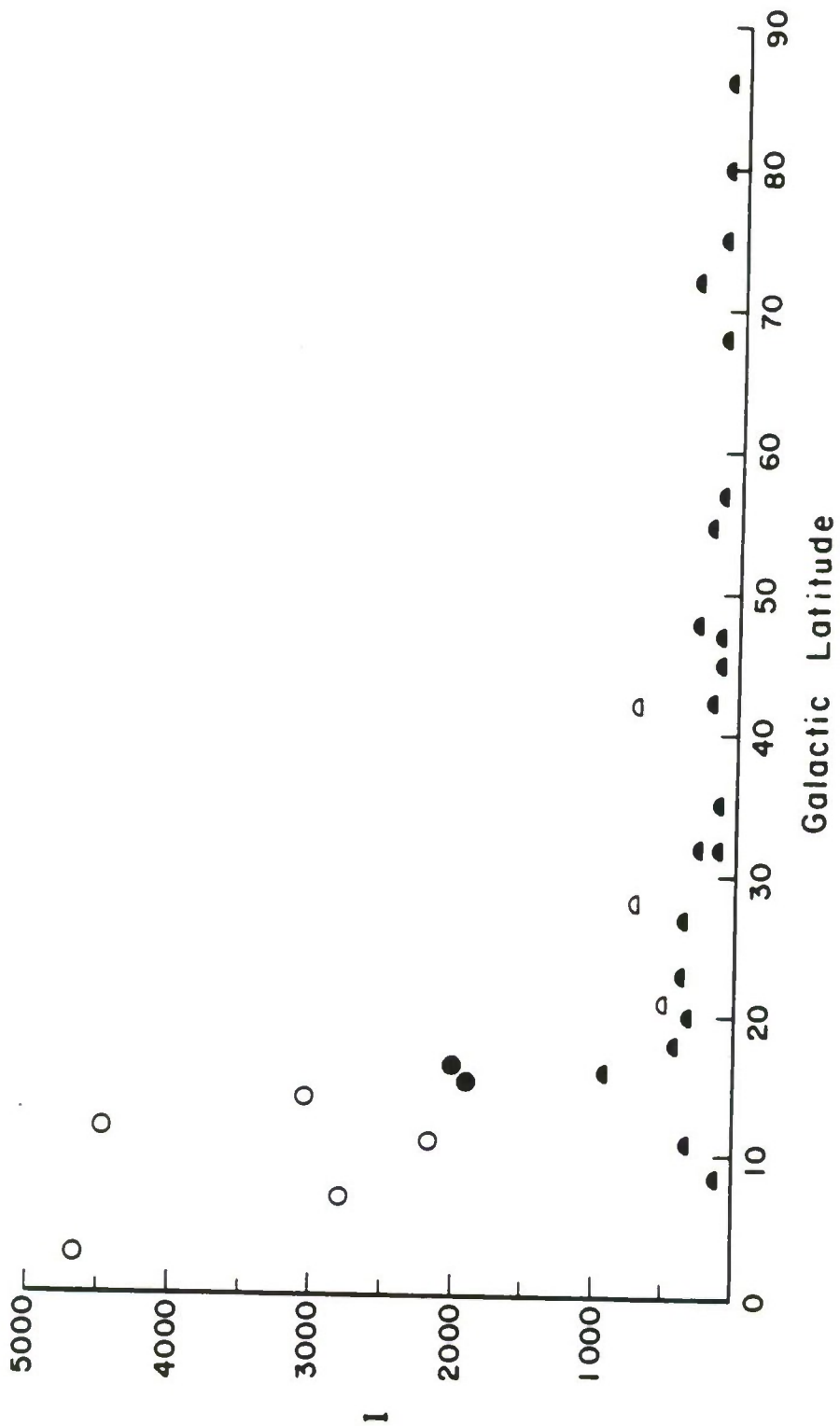


Figure 12 Voyager observations of cosmic background from Holberg (42), (filled symbols), and Sandel et al (10) (open symbols); upper limits are given by the lower edges of the semicircles. The Voyager limit on the background at latitudes above 30° is 100 units.

neutrino decay radiation. Results on neutrino decay from supernova 1987A are given by Chupp et al (15) and Kolb & Turner (58). Related discussion appears in Madsen & Epstein (65). If neutrinos have nonzero masses, they may oscillate (e.g. 5). There is the suggestion by Bahcall and Bethe, as reported by Nash (84), that Soviet study of solar neutrinos implies oscillation and hence a nonzero mass.

Sciama's photons also help with a problem that is faced by the $L\alpha$ recombination origin, suggested above to be the source of the longer-wavelength background. To get adequate intensity requires considerable clumping [although probably not too much to violate an important observational constraint by Martin & Bowyer (66) on the uniformity of the ultraviolet background], and Sciama's photons would prevent cooling-time difficulties that otherwise arise. Of course if Sciama's photons are the ultimate energy source of a background of redshifted $L\alpha$ radiation, that would destroy most or all of his photons!

Returning to the data in Figure 12, the positive detections below $|b| = 17^\circ$ are important: what is the source of this radiation? One particular observation, the 2000 unit observation in Ophiuchus at $b = -16.^\circ3$, is especially valuable, as it involves a long, slow, spatial scan, over all of which the flux is seen (42). Thus we have decisive evidence for a truly diffuse origin. Holberg analyzes the spectral appearance of this source, concluding that this background ultimately arises from stellar sources of early spectral type. I assume, therefore, that what we are seeing is 2000 units of diffuse cosmic ultraviolet background radiation arising from the light of OB stars scattering from interstellar dust. The location on the sky is near one end of the "bright half" of the Gould belt shown in Figure 7. The other six positive detections in Figure 12 all occur near Orion, that is, at the *other* end of the bright part of the Gould belt; also, *none* of the upper limits is at a location near the bright half of the Gould belt. Additional observations at other locations along the bright half of the belt would be of great value.

So we have a compelling case for the detection of *some* diffuse ultraviolet background radiation that surely has its origin in the light of OB stars scattering from interstellar dust. That makes even more interesting the fact that such radiation is not seen by *Voyager* at moderate or high galactic latitudes (Figure 12) (and also, notice, it is not seen at two low-galactic latitude locations that are in the

"dim half" of the Gould belt.) Why is no such radiation seen? There is certainly dust at many locations at high galactic latitudes, from *IRAS* observations, and from interstellar polarization studies. A natural answer is that the grains strongly forward-scatter the radiation out of the galaxy. This would require that the sources of the positive detections in Figure 12 be behind the scattering dust, which is of course possible.

In ending this section which has been positive in its discussion of the *Voyager* data it is important, however, to point out some of the difficulties encountered with them. In the analysis of a data sample (Section 2) we discussed a variety of contaminants -- airglow, stars, and dark current -- that may create a false diffuse ultraviolet background. The contrary can not occur: a spectrophotometric system, if it has demonstrated inflight the correctness of its calibration, can hardly fail to detect a true diffuse background if it is there. Therefore, when two diffuse background experiments that have been pointed at the same celestial location disagree, the burden of proof lies, of course, with the experiment that claims the higher background.

In this light, consider again the *Voyager* results. In his Ophiuchus scan, Holberg provides convincing proof that his signal is truly diffuse background. But such a proof is absent for the "fixed-location" positive detections in the Orion region by Sandel et al (101). In particular, there exists the possibility that what is being detected is not diffuse background radiation but direct radiation from a star, or stars, in the field of view. The *Voyager* (lowest) upper limits correspond to permitting one unreddened B0 star of magnitude 15.5 to be in the field of view (43). A false background of 3000 units would therefore require an unrecognized unreddened 11.8 magnitude B0 star (or several somewhat reddened such stars) to be in the field of view.

Why should that occur in Orion, and not elsewhere? For the very same reason that the claims of a diffuse background in that region of sky must be seriously entertained: that is where exceptionally large numbers of hot stars are located (Figure 7).

We turn next to the important spectral region, 1216 to 1800 Å, where many conflicting observations exist.

5. THE BACKGROUND 1216 TO 1800 Å

5.1 *Example of a Data Set*

A very attractive set of sounding rocket diffuse ultraviolet background radiation data at 1560 Å is provided by Onaka (86) and is shown in Figure 13. These data hold considerable potential for being an important measurement, and they are of a character that permits useful discussion in this section.

The potential of these data for being particularly important, stems from the use of an imaging detector (87), which means that concerns about point-source contamination are minimized. Figure 13 shows a background intensity of ~400 units, consistent with the Johns Hopkins *Aries* rocket result at longer wavelengths, reported above. With the *Voyager* results just reviewed the case for an origin in redshifted hydrogen L α radiation is strengthened somewhat.

However, we also see in Figure 13 some dependence of the diffuse ultraviolet background on neutral hydrogen column density. Such dependences have been reported before; the usual interpretation is that the correlated portion of the signal is due to the light of OB stars in the Galactic plane scattering off of dust located above the Galactic plane. The correlation with neutral hydrogen column density occurs because of the well-known correlation that exists between neutral hydrogen column density and dust (11, 111).

The theory of such dust-scattered radiation is given by Jura (55). A major problem with the Jura model when it is used at moderate Galactic latitudes is its assumption of a uniform longitude dependence in the original Galactic plane source. We have seen, in Figures 7, 8, and 9, that that assumption is wrong. Nevertheless, Jura's model is useful for discussion as a first approximation. Jura's theory has been applied by Onaka to the data of Figure 13, giving $a(1 - g) = 0.065 \pm 0.015$, where a is the albedo of the dust grains, and g is the heuristic asymmetry factor of Henyey & Greenstein (40). Negative values of g correspond to predominant backscattering. Even quite small positive values of g indicate rather strong forward scattering.

There has long been widespread agreement, which may be wrong, that the albedo of the grains in the far ultraviolet is high; that $a = 0.5$ may even be an underestimate. This view arose from

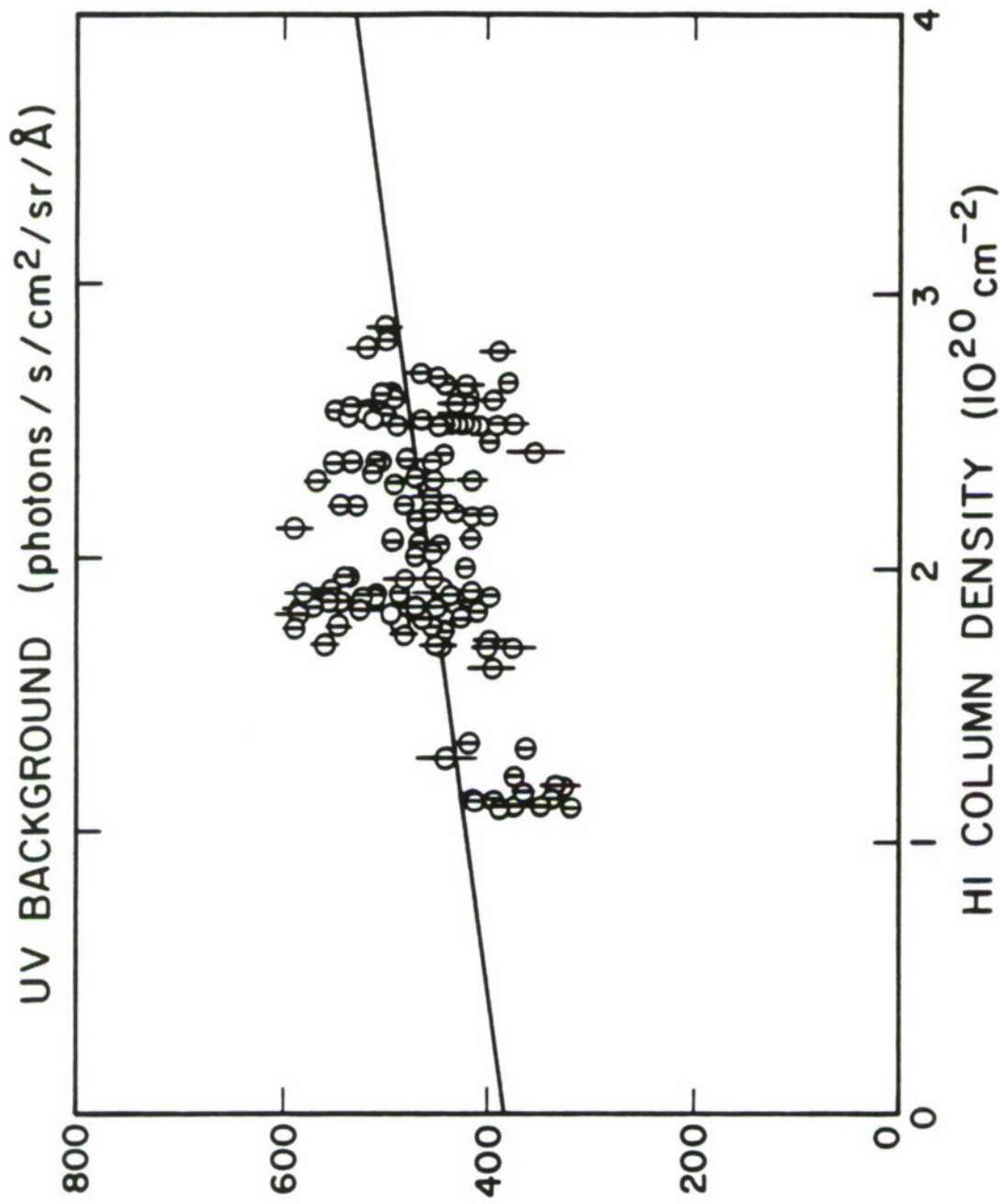


Figure 13 Rocket measurement of the diffuse ultraviolet background by Onaka (86). The general level agrees well with the background at longer wavelengths in Figure 11, but some correlation with neutral hydrogen column density appears. This figure is from (86), with permission.

theory and observation (70 and reference therein to 62). It is supported by an ultraviolet photograph of Orion (14) that seems to show a bright general diffuse glow, and also by the comparison of the *Apollo 17* ultraviolet radiation field (34) with that of *TD-1* (27) which shows an excess that Henry (31) attributed to bright low Galactic latitude diffuse Galactic light. If we do accept for the moment that $a = 0.5$, Onaka's data provide $g = 0.87 \pm 0.03$, which is very strong forward scattering.

What would *Voyager* have seen, if this interpretation of Onaka's result is correct? Extinction is stronger at *Voyager* wavelengths of $\sim 1100 \text{ \AA}$ than it is at Onaka's 1560 \AA (105, 118). Of course *Voyager* does not see the extragalactic component of ~ 380 units that Onaka's observation implies, but we have assumed that this is because the extragalactic source does not continue below $\sim 1216 \text{ \AA}$. The question we are addressing is this: should *Voyager* have seen the dust-scattered component? A simple calculation, assuming no change in a or in g between 1560 and 1100 \AA , predicts a signal for *Voyager* of only ~ 90 units, which is just inside the *Voyager* upper limit.

The predicted intensity will be less if the ultimate source, the far-ultraviolet radiation field, should decline shortward of $L\alpha$. The observed spectrum of Henry et al (34) suggests that no large decline occurs.

Next, Onaka's relation can be used (for discussion purposes) to predict what should be seen from dust scattering at lower galactic latitudes. This must be done with caution, as Jura's theory does not include multiple scattering, so consider what should be seen at galactic latitude 40° , where hydrogen column densities lie in the range $4 - 10 \times 10^{20} \text{ cm}^{-2}$ (29). The prediction is $500 - 800$ units, depending on longitude.

Finally, if indeed there are $500 - 800$ units present at $b \sim 40^\circ$ (of which $120 - 420$ are due to dust), what should *Voyager* have seen at those latitudes? The answer is, $200 - 700$ units, depending on longitude! No such radiation is observed (Figure 12), and so either this interpretation of Onaka's result (and some others described below) is incorrect, or the grains change in their albedo and/or g value substantially between 1560 and 1100 \AA . The grains may of course change, but the change required for, say, 300 units due to dust at 1560 \AA is rather large: at 1100 \AA $a(1-g) \sim 0.015$, which gives

$a = 0.1$ for $g = 0.87$, and even lower a for smaller values of g , at this wavelength.

Yet we have a very well established *Voyager* observation of diffuse Galactic light (that is, starlight scattered from dust) in Ophiuchus, described above. *Voyager* was fully capable of detecting light scattered from dust, if it is there. The data from *Voyager* are therefore facts of life which those who wish to ascribe much of the ultraviolet background to dust scattering must explain.

5.2 *Apollo 17*

The last *Apollo* mission to the moon carried (22) a far-ultraviolet Ebert-Fastie spectrometer that was used by Henry et al (35, 37) and Anderson et al (2) in the study of the diffuse ultraviolet background. The data from the *Apollo 17* spectrometer suffered from an unexpected very high dark count rate coming from cosmic rays. Fortunately the dark count rate was established with precision and was very constant. Grating-scattered $L\alpha$ radiation was also present in the data but we showed that because the $L\alpha$ intensity was measured on every scan, scattered light could be removed with confidence. After these corrections, the result was a very black sky indeed, at moderate and high latitudes.

Unfortunately a third correction, not so convincingly determined, was made: that for direct starlight. If we had it all to do over again, knowing what we know now, we probably would not make a correction for starlight, because the average surface brightness due to stars at moderate and high latitudes, in all regions except for those near the location of only six or seven isolated bright stars, is very low. Our corrections were made by extrapolation of visible light star catalogue data to the ultraviolet. Landsman (60) located seven $12^\circ \times 12^\circ$ regions where the surface brightness due to *TD-1* satellite stars (that is, *directly measured* ultraviolet fluxes) is in the range of only 60 to 114 units, and he also reevaluated, using the *TD-1* satellite data, the stellar corrections that were made in some *Apollo 17* papers. For example, Henry et al (35) observed two $12^\circ \times 12^\circ$ regions in Draco ($b = +26^\circ$) and Taurus ($b = -13^\circ$). Henry et al reported no detectable diffuse Galactic light. The much better Landsman corrections give celestial scattered light at $b = 26^\circ$ of <200 units, and at $b = -13^\circ$ of 700 to 1000 units.

By coincidence, the $12^\circ \times 12^\circ$ Taurus target includes one of only two positive *Voyager* detections reported by Holberg (42), of 1900 units, near the edge of the *Apollo 17* target that is nearest Orion.

Landsman also checked the stellar subtractions for the *Apollo 17* positive detection (see Figure 2), at 270 units, of the cosmic background (37), finding an average overcorrection of 92 units at 1455 \AA and 140 units at 1565 \AA . The stellar correction is larger and Henry's overcorrection (due to use of extrapolated visible data) is larger at the longer wavelengths, which suggests that the drop they reported in the background at their longest wavelength is spurious.

Anderson et al (2) and Henry (32) reported that *Apollo 17* mapping of about one third of the sky showed that the diffuse cosmic ultraviolet background was zero for $|b| > 20^\circ$, with an error bar that was, as just described, not very well determined. The limited check by Landsman suggests that an upper limit of 400 units for $|b| > 30^\circ$ is justified. (The region of sky observed unfortunately did not include the region in Ophiuchus where the most convincing *Voyager* diffuse background occurs.)

The *Apollo 17* upper limit of 400 units is less than the 500 to 800 units that was "predicted" in my use of Onaka's relation as an example for discussion purposes, and is consistent with only our "extragalactic component" being present.

5.3 Example of a Conflict

The data that have been discussed so far accord well with a picture in which (1) a uniform extragalactic background of ~ 400 units is present from near 1216 \AA to at least 3200 \AA ; (2) only an upper limit of 100 units exists below 1216 \AA ; and (3) no strong evidence exists for any starlight scattered from dust, except at the very lowest Galactic (or Gould) latitudes, and in a limited longitude range.

In this section we present an example of conflicting data. We focus first on a case in which several observers look at the same location, with similar field of view, and at the same wavelength.

Weller (114) published an important measurement of the diffuse background made from a spacecraft whose altitude (130,000 km) was so high that airglow and time-variable dark count could not be deleterious factors, and important because the instrument field of view was large (8° FWHM), which made the stellar correction very insensitive to precise knowledge of any faint stars that might inadvertently be in the field of view. Weller compared his results (Figure 14) with *Apollo 17* results, with results from the *Apollo-Soyuz* mission (91) (see next section) and also with another Johns Hopkins *Aries* rocket result (1). As is apparent in Figure 14, the results from Weller, *Aries*, and *Apollo 17* agree on a low background, of order 300 units; while in contrast *Apollo Soyuz*, in repeated measurements, finds backgrounds of 900 to 1500 units.

In earlier discussion I argued that a large false background is not unlikely in any experiment while the reverse (missing a large signal that is actually there) is unlikely. It is the *Apollo-Soyuz* result that gives the high count rate. If the "low-background" observers subtracted out their signal, erroneously attributing it to stars (as occurred to some extent in *Apollo 17*), then the argument does not hold. But in the case at hand, the total stellar corrections are much less than the claimed *Apollo-Soyuz* backgrounds, and it would seem that no reasonable case can be made that the *Apollo-Soyuz* results are correct.

5.4 *Apollo-Soyuz*

What are the data from *Apollo-Soyuz* that are in dispute? They are presented in Figure 15, for the northern galactic hemisphere. Detections at a level of ~ 300 units are shown in that diagram over large regions at moderate and high Galactic latitudes, and cosmic backgrounds of thousands of units are also seen at all Galactic latitudes, including the highest.

These results contradict the many results discussed in the previous sections. From that discussion one can doubt any detections in Figure 15. Nevertheless, Paresce et al (92) attempted to extract from among the 3200 total *Apollo-Soyuz* observations, some positive detections that might contain astrophysical information. They located 128 measurements that provided four correlations of intensity with hydrogen column density. A critical discussion of the *Apollo-Soyuz* data as analysed by Paresce et al (92) is given elsewhere (32).

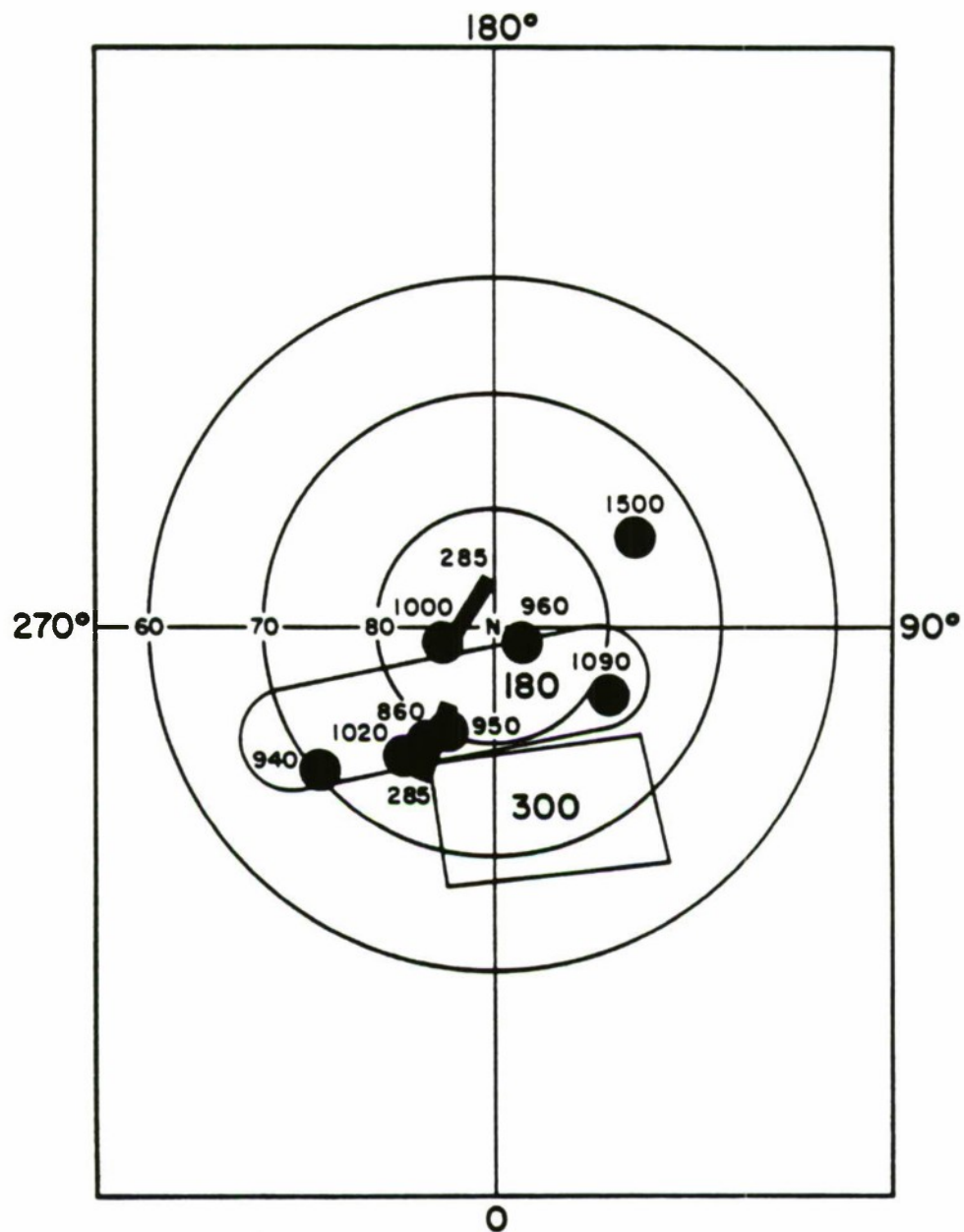


Figure 14 Four observations of diffuse ultraviolet background radiation near the north galactic pole are compared by Weller (114). The data of Weller (114, *oval* at 180 units), Henry et al (37, *quadrilateral* at 300 units), and Anderson et al (1, *filled rectangles* at 285 units) agree reasonably well, while *Apollo-Soyuz* observations (*filled circles*) give much higher values. This figure is from Weller (114), with permission.

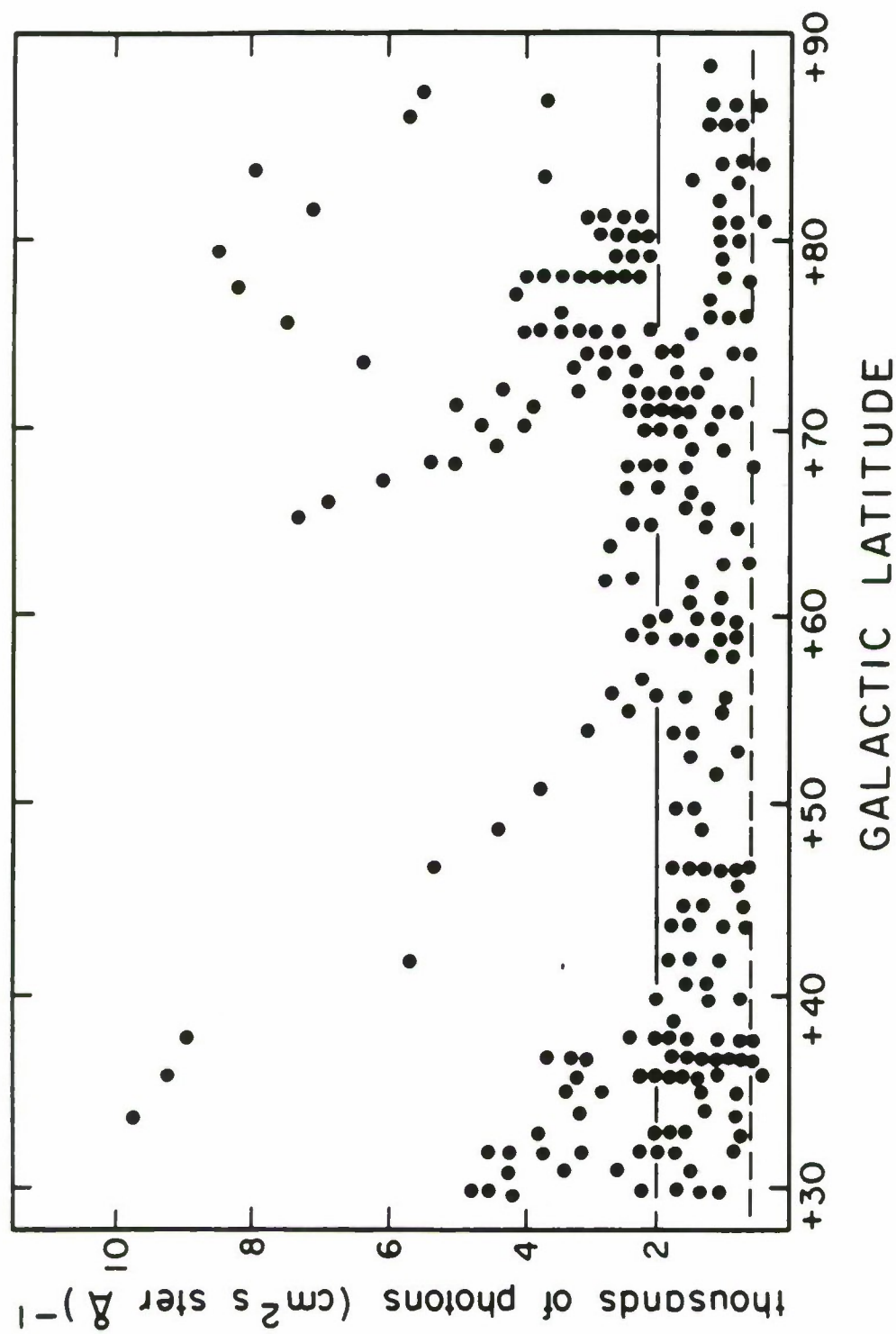


Figure 15 Henry (32) translated the *Apollo-Soyuz* count rates of Paresce et al (91) into units and presented this and a corresponding figure for the southern galactic hemisphere. It is argued in the text that the lower bounds of ~300 or 400 units are of great significance in the study of diffuse ultraviolet background radiation.

We are left with upper limits from *Apollo-Soyuz*. But nevertheless these upper limits are of great importance in trying to understand the origin of the diffuse ultraviolet background, now to be discussed.

5.5 Evidence For Scattering From Dust?

Fix, Craven & Frank (25) used the imaging experiment aboard *Dynamics Explorer 1* to obtain the ultraviolet background data that appear in Figure 16. In this experiment the use of an imager renders stars less of a concern; also use of a very high orbit means that airglow and time-dependent dark current should not be factors. The residual they report at 1500 Å, shown in Figure 16, consists of a component that is independent of Galactic latitude, plus a component that shows a clear dependence on Galactic latitude. A natural interpretation is an extragalactic component plus a component originating in the light of Galactic-plane OB stars scattering from dust. The correlation with neutral hydrogen column density that they find gives the strength of the extragalactic component as 530 ± 80 units, in reasonable agreement with other determinations (longward of 1216 Å) reported above.

Consider first these observations at face value and ask, what can we conclude concerning the optical properties of interstellar dust? The argument has already been rehearsed above: the lack of detectable signal from *Voyager* at $b = 40^\circ$ means that a drastic change must take place in the scattering properties of the interstellar grains between 1500 and 1100 Å, in the sense that either the grains have a much lower albedo at 1100 Å, or are much more strongly forward scattering at 1100 Å, or some combination of the above.

Can the observations be criticized? Note that only photometry is involved, not spectroscopy, so the signal has no internal character that can be examined in hope of gaining an understanding of the signal's origin. Next, the authors determine their dark current through studying the count rate with different filters in place, and say that the count rate due to cosmic rays should be independent of the filter. But this is not necessarily so, because part of the dark count could well originate in ultraviolet fluorescence in the material of the filter itself, and it is known that different filters may have very different rates of fluorescence. If this is a factor,

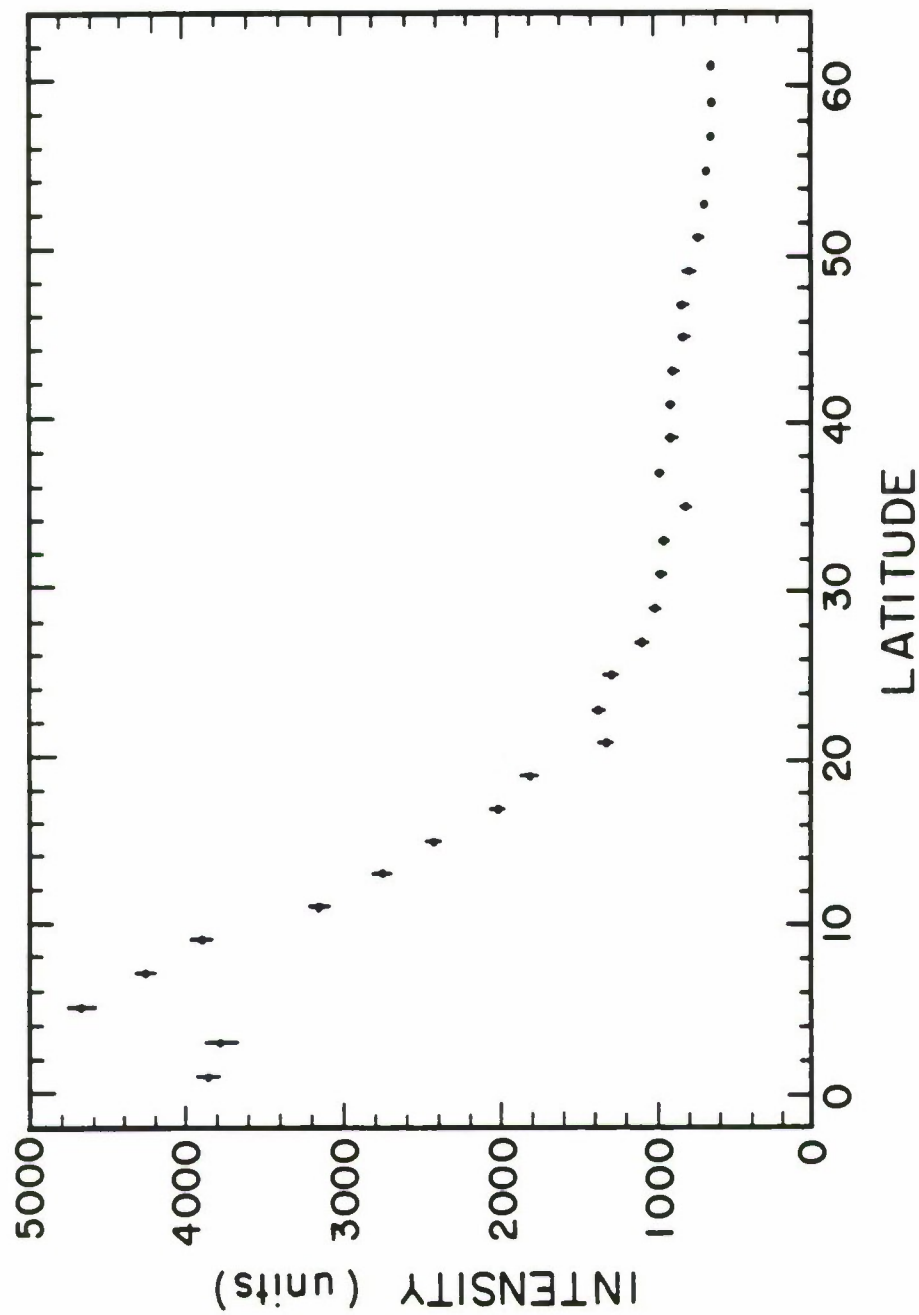


Figure 16 Fix, Craven & Frank (25) obtained these data showing the diffuse ultraviolet background as a function of galactic latitude. The distribution is very smooth, and at moderate latitudes exceeds the *Apollo-Soyuz* upper limits of Figure 15. This figure is from Fix et al (25), with permission.

however, it will only affect the "extragalactic" component, not the "dust scattering" component of the signal. With those exceptions, there is nothing else internally to criticize in the observations. In particular, the observations lack the "patchy" appearance expected if undetected-star contamination is a problem.

Externally two problems exist with the data. The first is the disagreement with the *Apollo 17* upper limit, at moderate latitudes, of 400 units at the same wavelength. Fix et al find 800 units. In view of the stellar correction problem on *Apollo 17*, however, some do not find this argument compelling. Less easy to dismiss is the clear disagreement with the upper limits of 300 units (91) from *Apollo-Soyuz*, that appear in Figure 15. As argued before, the problem is to prove that the higher background is not spurious; it has been argued above that the Berkeley *upper limits* are reliable. Also, the data shown in Figure 16 represent the average, with $\pm 1\sigma$ error bars, of four different cuts through the galactic plane, so "looking in different directions" is unlikely to be the answer as to why Figure 16 differs from Figure 15, but this problem cannot be studied in detail because the galactic longitudes of the Berkeley observations are not published.

5.6 *More Evidence For Scattering From Dust?*

Joubert et al (54) present data (Figure 17) that also seem to argue for an origin of the diffuse ultraviolet background in an extragalactic component (of 400 units at 2200 Å, and 700 units at 1690 Å, at $N_H = 0$), plus a component that results from dust scattering.

If we accept the dust-scattering component as real because of its correlation with N_H in Figure 17, then we must repeat our remarks about the very different optical parameters that must obtain for the interstellar grains at 1100 Å. On the other hand, there is a profound difference between the data of Figure 17 and those of Figure 16. In Figure 17, where each point represents an average over a large ($30^\circ \times 30^\circ$) region of sky, a large scatter appears; a scatter entirely absent in Figure 16. That the Joubert et al data scatter is real, has been reaffirmed by Lequeux (61) and is inexplicable in terms of a dust scattering origin. It could be due to a dust-scattering origin for the lower envelope in Figure 17 plus a highly patchy extragalactic background. (Even *that much* light

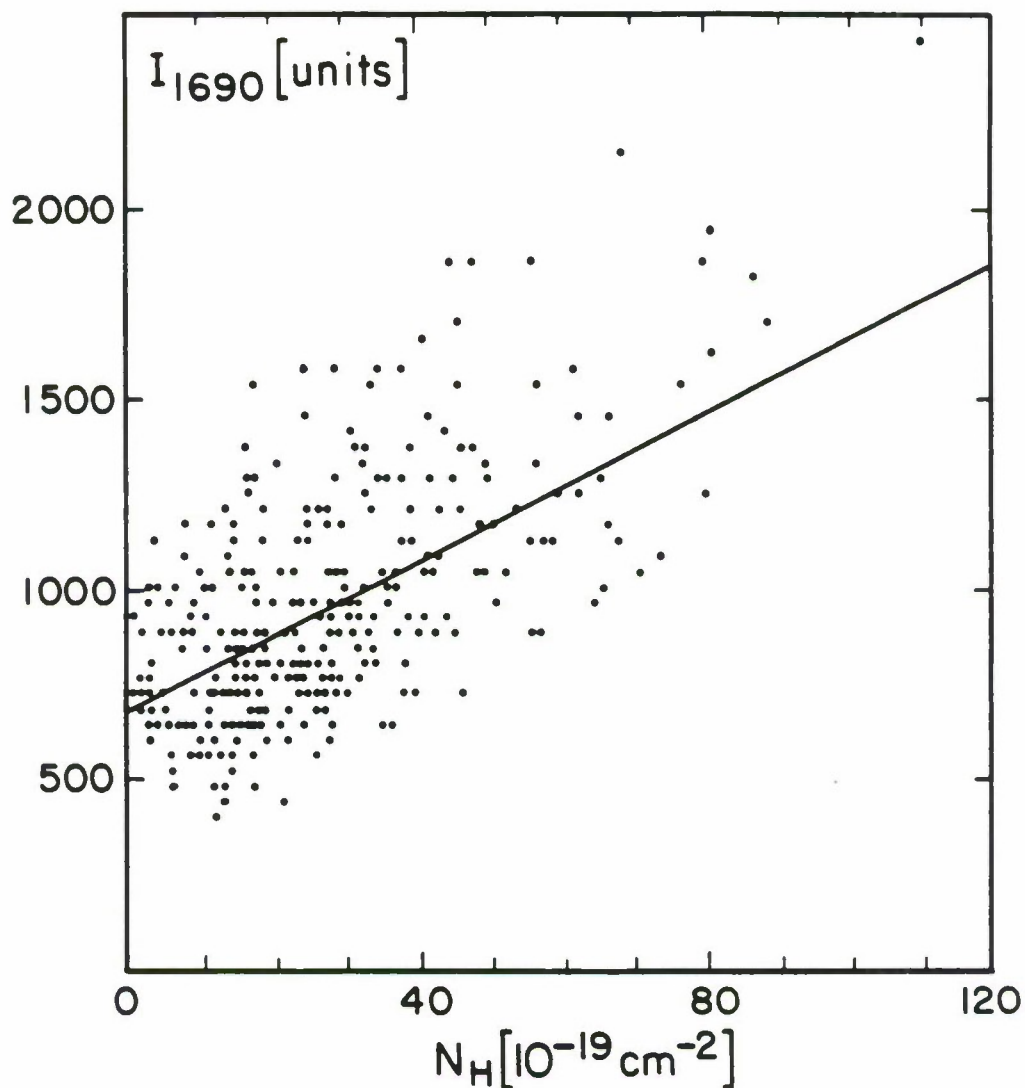


Figure 17 Joubert et al (54) obtained this dependence of cosmic ultraviolet background radiation on neutral hydrogen column density. Each point represents an average over a 30-square degree region. The scatter is real and must be compared with the smoothness of the data in Figure 16. *Apollo-Soyuz* data of Figure 15 give many well-established upper limits of 300 to 400 units. Experiments that individually seem clearly to indicate the presence of dust scattering disagree with each other profoundly in detail. This figure is from Joubert et al (54), with permission.

originating in dust scattering would require a large change in grain optical properties with wavelength.)

The data of Figure 17 again disagree with the *Apollo 17* upper limit of 400 units, and with the more reliable *Apollo-Soyuz* upper limits of 300 units, because the signal in Figure 17, though patchy, is never as low as 300 units, even at moderate Galactic latitudes.

The Joubert et al data (54) came from an experiment located at very high altitude, so time-variable dark current should not be a problem. However, pointing was not completely stable, and undetected faint stars would of course give a patchy appearance as appears in the data. With the Joubert et al field of view of 4×10^{-4} sr, an undetected unreddened 9th magnitude A0 star would produce a false background of 300 units, while a 10th magnitude B5 star would give 870 units. The experimenters have made every effort to assure themselves that that is not what is happening.

5.7 More Observations

The purpose of parts of the preceding discussions concerning various past experiments was to emphasize that truly reliable data concerning the diffuse ultraviolet background are hard to come by. In particular, one cannot simply accept data as they are presented; one must look very critically at the circumstances under which they were obtained to judge the likelihood that the data deserve serious attention. Consider now four additional data sets.

5.7.1 OAO-2 The pioneers of the study of diffuse ultraviolet background radiation were Lillie & Witt (62), and their conclusions concerning the ultraviolet albedo a and the scattering parameter g , for interstellar grains are still widely used. My concerns (33) about their data have centered on the extremely small (8.5×10^{-6} sr) OAO-2 field of view, and the time-variable dark current due to low Earth orbit through the radiation belts. The OAO-2 was intended for the study of point sources, not low-surface-brightness extended backgrounds. Such experiments, in low Earth orbit, are prone to problems of false *patchy* backgrounds, and a patchy background is exactly what Lillie & Witt report. In view of this their conclusions must be confirmed by other experiments that are optimized for the study of diffuse backgrounds rather than point sources.

5.7.2 BERKELEY ARIES ROCKET Jakobsen et al (53) made rocket measurements, at altitudes below 250 km and with broad-band photometers, of a region at constant galactic latitude but having spatially variable hydrogen column density. Intensities of 600 to 3000 units are reported, and correlations, of varying strength, of intensity with column density, are reported at all three wavelengths (1590, 1710, and 2135 Å) observed. Murthy, Henry & Holberg (83) have used the *Voyager* ultraviolet spectrometer to make observations at the beginning and at the end of the Jakobsen et al scan areas. They obtain only the usual *Voyager* upper limits. The interpretation of the differences between the two studies will appear in upcoming work by Murthy et al (83). The reason is either that the Jakobsen et al results are incorrect, or that different sources are involved at the different wavelengths.

5.7.3 PROGNOZ The *Prognosz* spacecraft had an orbit that took it very far from Earth. Solar system $L\alpha$ was admitted to the spectrometer but could be corrected for. The data have been presented in a number of different forums, and it has been difficult to follow the details of data selection and treatment. The latest presentation (119) shows excellent agreement between some of the data, and some of the data of Paresce et al (92).

The authors also point to a possible origin for the contamination which we suggested above is present in the data of Paresce et al (91, 92). The Russian authors refer to a photograph showing a "huge cloud of heavy molecules which surrounded the combined *Apollo-Soyuz* spaceship and produced strong scattering in the experiment of Paresce et al (92)".

5.7.4 TD-1 The *TD-1* field of view was very small (1.7×10^{-5} sr), and time-variable dark current was a serious problem. The *TD-1* data are mentioned here only for reference (75, 76).

5.8 UVX

We consider now in some detail the *UVX* experimental results and their bearing on the previous results of the Berkeley group where bright patches of thousands of units over the sky are reported and those of the Johns Hopkins group where ~400 units are reported for $|b| > 30^\circ$. The dual experiment involved co-aligned spectrometers, although unfortunately the targets were only eight locations in the sky.

5.8.1 BERKELEY *UVX* BACKGROUND INTENSITIES Extraction of the Berkeley *UVX* background intensities is complicated by claims of emission features in the spectra (discussed below) and fragmentary publication of the data. Only in the target called CLEAR (which is target 1 in *all* numbering schemes) has a complete spectrum been published [Figure 3 of Martin & Bowyer (67)], although a fairly complete picture can be obtained for four additional targets from Figure 1 of Martin, Hurwitz & Bowyer (68). For all targets, Figure 1 of Bowyer (10) gives an average intensity (excluding all claimed emission features) that is ~ 1100 units for targets with $|b| < 30^\circ$ and is < 700 units for higher latitude targets. Figure 4 of Hurwitz, Bowyer & Martin (47), identical to Figure 1 of Hurwitz, Bowyer & Martin (48) gives continuum intensities at $1580 \pm 15 \text{ \AA}$ of ~ 1400 units for targets with $|b| < 30^\circ$ and < 800 units for higher latitude targets; these intensities exclude claimed high-ionization line emissions, but seem to include claimed H₂ fluorescence emission (see below).

How reliable are the Berkeley intensities? Their experiment is of excellent design, the best that has ever been flown for the study of diffuse ultraviolet background radiation. Control of dark current is excellent, and an imager was used. Preliminary publication of the Berkeley data (49) showed six observations, at hydrogen column densities $< 6 \times 10^{20} \text{ cm}^{-2}$ (presumably these are the six targets that have $|b| > 30^\circ$), with background intensities at 1800 \AA that are all less than 300 units. Asked to account for the difference at the 1989 Heidelberg IAU Symposium #139 on background radiation, Berkeley workers indicated "overenthusiastic stellar subtraction" as the culprit and that the Berkeley workers later decided that their higher flux levels were real. One must accept the finally published intensities as most authoritative.

So from *UVX*, the Berkeley group finds no trace of the intense bright patches that were reported earlier from *Apollo-Soyuz* and that are shown in Figure 15. The Berkeley *UVX* data do show a somewhat higher cosmic background at middle latitudes (~ 750 units at $b \sim 40^\circ$) than the Johns Hopkins group has claimed.

5.8.2 JOHNS HOPKINS *UVX* BACKGROUND INTENSITIES Murthy et al (81 and especially 82) report intensities in the range 400 to 1000 units for four out of six *UVX* targets at moderate or high galactic latitudes. There is no detailed correlation between the Berkeley and

JHU intensities on these targets. The Johns Hopkins *UVX* intensities should be less reliable than the Berkeley *UVX* intensities because (a) before launch, the capability to obtain any dark count measure at all was removed from the Johns Hopkins experiment, (b) the Johns Hopkins scanning spectrometer is potentially vulnerable to faint stars in the slit, and (c) noise contamination was often present in the Johns Hopkins short-wavelength spectrometer (only).

The final conclusion is that neither experiment saw the "bright patches" of many thousands of units that had been previously reported by Berkeley (90, 91). Of particular interest is the target named ERIDANUS of Murthy et al (81, 82). Paresce et al (90) reported background intensities in Eridanus, from *Apollo Soyuz*, of ~ 6000 units. The location of the *UVX* ERIDANUS target was selected by Berkeley, and turns out to be rather removed from the Paresce et al (90) location. At ERIDANUS, Murthy et al (81) find 200 ± 200 units in their short-wavelength spectrometer, while Murthy et al (82) find 650 ± 200 units in their long-wavelength spectrometer. By some detective work from the published Berkeley *UVX* data one can deduce that the correct number from the Berkeley experiment is about 750 units. However, the *UVX* observations were made at a different location than where Paresce et al (90) had previously reported a background of 6000 units; hence these three observations do not decisively rule out that earlier extraordinary result.

5.8.3 MOLECULAR HYDROGEN FLUORESCENCE Witt et al (116) observed ultraviolet fluorescence of H_2 in the nebula IC63. The fluorescence is stimulated by the radiation from a very hot star, γ Cas, located near the nebula. It is certain that interstellar molecular hydrogen exists at moderate and high galactic latitudes, and that hydrogen is bathed in the intense (27) ultraviolet radiation field of the galaxy. Thus, anticipation of the detection of H_2 fluorescence in the diffuse ultraviolet background is understandable, and Martin, Hurwitz & Bowyer (68) present statistical and circumstantial evidence for the presence of molecular hydrogen emission in five of their *UVX* targets.

From the amount of molecular hydrogen emission that is deduced by Martin et al, one can estimate the amount of diffuse background that would be seen by *Voyager*. Sternberg (120) shows that about two thirds of the fluorescent radiation will fall in the region below $L\alpha$, where *Voyager* is most sensitive, and only one third

will occur at longer wavelengths where Martin et al claim a detection. However, *Voyager* should have seen hundreds of units of diffuse background if the Martin et al result is correct but it has not (Figure 12). In particular, Murthy, Henry & Holberg (83) have taken observations with *Voyager* near the beginning and the end of the GRADIENT *UVX* target, which is where Berkeley reports the strongest molecular hydrogen emission. They obtain only the usual *Voyager* upper limits of ~100 units.

5.8.4 LINE EMISSION FROM HOT GAS Spitzer (106) suggested a hot corona for the galaxy, and ultraviolet absorption lines have been observed (e.g. 102) that might have that origin. Jakobsen & Paresce (52) have predicted the amount of collisionally excited line emission that would be produced by a hot corona of the galaxy (see also 93). Possible detection of such emission was reported by Feldman et al (24), and further evidence for such emission has been presented by Martin & Bowyer (67), in several of their *UVX* spectra.

The Feldman et al observation was statistically marginal, but it has in its favor the fact that the data set was very well-behaved and free of contamination. The Berkeley data should be of much higher quality, but they have not yet been published in detail. The complete spectrum has been published for only a single target.

5.8.5 SCATTERING FROM DUST When, as mentioned above, Paresce, McKee & Bowyer (92) found, from a small subset of the *Apollo-Soyuz* data of Paresce et al (91), four different correlations of intensity with hydrogen column density in different regions of the sky, they pointed out that such differences may be due to intrinsic variability over the sky of the gas-to-dust ratio and of the galactic plane light source. One can see in Figures 7, 8, and 9 how strong in fact the latter variation actually is! The eight *UVX* targets are scattered over the sky, particularly with respect to the bright half of the Gould belt, which is likely the dominant original source of any dust-scattered light at moderate and high latitudes. Because of the scatter of the location of the *UVX* targets relative to the bright half of the Gould belt, no simple correlation between intensity of scattered light and hydrogen column density can be expected for the *UVX* targets. Therefore, it would seem that this kind of analysis by Hurwitz, Bowyer & Martin (47, 48), that takes no account of either the Gould belt or any anisotropy in longitude of the radiation field can only be an approximation of detailed trends that may exist.

6. CONCLUSIONS

In this review we have made an effort to show that the conclusions from most observations of the diffuse ultraviolet background should be treated with reserve. The situation is made worse because sometimes only fragments of the data are published. The three admonitions I made when I reviewed this field the last time (33) still apply, and are:

1. It is crucial that every detail of the experiment, the data processing, and the analysis be published; otherwise, a critical assessment is not possible, and the results cannot be said to be established.

2. All data should be published, including data that were excluded from analysis for various reasons. A critical assessment is stymied otherwise.

3. The coordinates of claimed bright and dark spots on the sky should be published so that detailed consistency of results between different experiments on the same targets can be tested.

6.1 *Spectral Structure in the Diffuse Ultraviolet Background*

The suggestion by Feldman et al (24) and of Martin & Bowyer (67) that line emission from interstellar gas, or a hot halo of the galaxy, has been detected if true would, of course, be important but cannot yet be taken as an established fact.

The discussion of Martin, Hurwitz & Bowyer (68) of fluorescence radiation of H_2 from the interstellar medium would seem to be incorrect, otherwise *Voyager* would have detected the radiation at shorter wavelengths. There is some controversy concerning the *Voyager* calibration (17), but all of the numbers that are quoted in this chapter employ the calibration of Holberg et al (44), which is conservative in the sense that the lowest *Voyager* upper limits that appear in Figure 15 would otherwise be substantially lower.

6.2 *Is There Light Scattered From Dust?*

As described above, many data sets, if considered in isolation, suggest that the light of the OB stars of the Galactic plane

scattering off of dust located at high Galactic latitudes has been seen. However, many of these data sets are contradictory.

Among all of the data sets in the 1216 to 1800 Å range the one subset that seem to be decisive is the large number of 300 unit observations of Paresce et al (91). [Henry (32) has pointed to a good reason that these observations should be considered to read 400 units, not 300 units.] It seems certain that these observations are correct, at least if they are treated as upper limits. These numerous upper limits are, in my opinion, the best evidence that there is no significant amount of light scattered from dust at moderate and high latitudes. This is not an unreasonable conclusion, because the *IRAS* observations of strong cosmic cirrus at 100 μm mean that the dust must be strongly absorbing at some wavelengths where there is significant energy input from stars in the Galactic plane.

I cannot explain the high intensities at moderate latitudes that appear in Figures 16 and 17, but the Paresce et al (91) data suggest that those intensities may be incorrect. For the future, a well-calibrated deep ultraviolet image of the optically reflecting dust cloud at $b = +40^\circ$ (100) would be sufficient to prove this view right or wrong.

The above remarks apply only to $|b| > 30^\circ$, but there is some evidence that even at the lowest latitudes there is very little light scattered from dust in that half of the Galactic (or rather, Gould) plane that is relatively free of stars that are bright in the ultraviolet (Figure 7). In the brighter parts of the Gould belt, a fairly bright diffuse background may be present. Of course at some level, it is inevitable that light scattered from dust must be present at high latitudes, but the claim here is that the amount is small compared with 400 units.

6.3 Diffuse Cosmic Ultraviolet Background Radiation

What is left? What is left is a background of ~400 units, which is present everywhere that has been observed at moderate and high galactic latitudes, and which is present everywhere from ~1216 to 3200 Å (and possibly beyond). This background is not present at wavelengths below ~1216 Å, where an upper limit of 100 units prevails.

This background, which may be extragalactic, may be spatially non uniform. The data of Murthy et al (82) suggest that, and there is an excellent observation by Martin & Bowyer (66) that also differs from the canonical value of 400 units.

I have suggested earlier a possible origin for such an extragalactic radiation. What is needed now, are precise new photometric and spectroscopic observations of this radiation, both to confirm it and to attempt to deduce its origin.

7. FUTURE DIRECTIONS

In the study of diffuse ultraviolet background radiation we need a sophisticated and systematic effort to spatially and spectrally map the entire sky. Just such an effort has been proposed by Kimble, Henry & Paresce (57).

Their proposed instrumentation offers not only unprecedented sensitivity, spectral resolution, and all the other good things, but also unprecedented attention to the sources of concern that I have described above. The proposed experiment has the defect of being confined to wavelengths longward of 1216 Å, but that seems to be where the signal is, and in any case, it is a defect of caution, as they do not wish to use a windowless detector nor do they wish to admit $L\alpha$.

A sounding-rocket experiment to confirm the *Voyager* upper limit shortward of $L\alpha$ would be of the very greatest value. In this review I depended on data from *Voyager*; and it would be important to see independent confirmation of those crucial upper limits. The experiment could use a very wide field of view, as the surface brightness due to all known stars at 1100 Å, at high galactic latitudes, is much less than 100 units.

ACKNOWLEDGMENTS

I am grateful to all of my collaborators and supporters over the years, particularly Paul D. Feldman and William G. Fastie. Partial support for this work came from NASA grants NAG5-619 and NAGW-1890 to The Johns Hopkins University, and from the SDIO Backgrounds Data Center, US Naval Research Laboratory.

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